Motivation, Status, and Plans for NSTX Upgrade

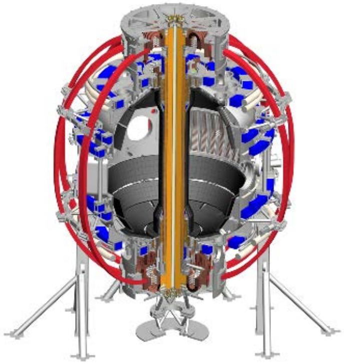
J. Menard, PPPL

For the NSTX-U Research Team

Fusion Energy Sciences Advisory Committee Meeting

Bethesda North Marriott Hotel & Conference Center

January 13-14, 2016



NSTX-U = National Spherical Torus eXperiment - Upgrade
Highly collaborative research program

Domestic (33)

College of William and Mary
Columbia University
CompX
Florida International Univ.
General Atomics
Idaho National Laboratory
Johns Hopkins University
Lawrence Livermore Nat. Lab.
Lehigh University
Lodestar Research Corporation
Los Alamos National Laboratory
Massachusetts Institute of Tech.
Nova Photonics, Inc
Oak Ridge National Laboratory
Old Dominion University
Princeton Plasma Physics Lab
Princeton University
Purdue University
Sandia National Laboratory
Tech-X Corporation
U. of California - Davis
U. of California - Irvine
U. of California - Los Angeles
U. of California - San Diego
U. of California - Space Sci. Lab.
University of Colorado
University of Illinois
University of Maryland
University of Rochester
University of Tennessee
University of Texas
University of Washington
University of Wisconsin

402 team members

290 scientists

(~70% non-PPPL)

55 institutions

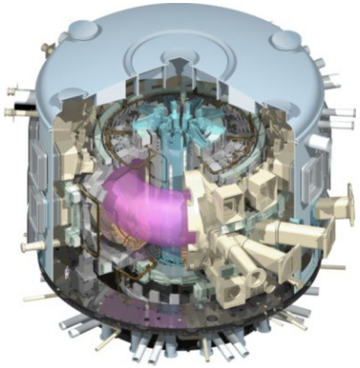
22 US Universities

International (22)

ASIPP
CCFE
FOM Institute DIFFER
Hiroshima University
Inst. for Nuclear Research
IPP-Czech Republic
Ioffe Physical-Tech. Inst.
JAEA
KAIST
Kyoto University
Kyushu University
NFRI
NIFS
Niigata University
Seoul National University
Tokamak Energy, LTD
TRINITI
UNIST
University of Costa Rica
University of Hyogo
University of Tokyo
University of York

NSTX-U Mission Elements:

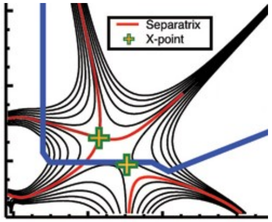
- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond



ITER

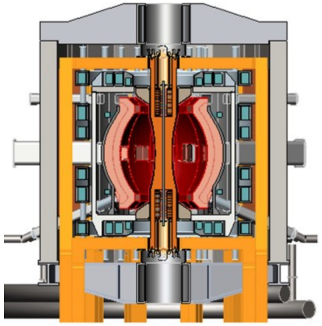
- Develop solutions for plasma-material interface (PMI)

Liquid metals / Lithium

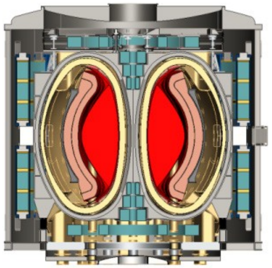


Snowflake/X

- Advance ST as Fusion Nuclear Science Facility and Pilot Plant



ST-FNSF / Pilot-Plant

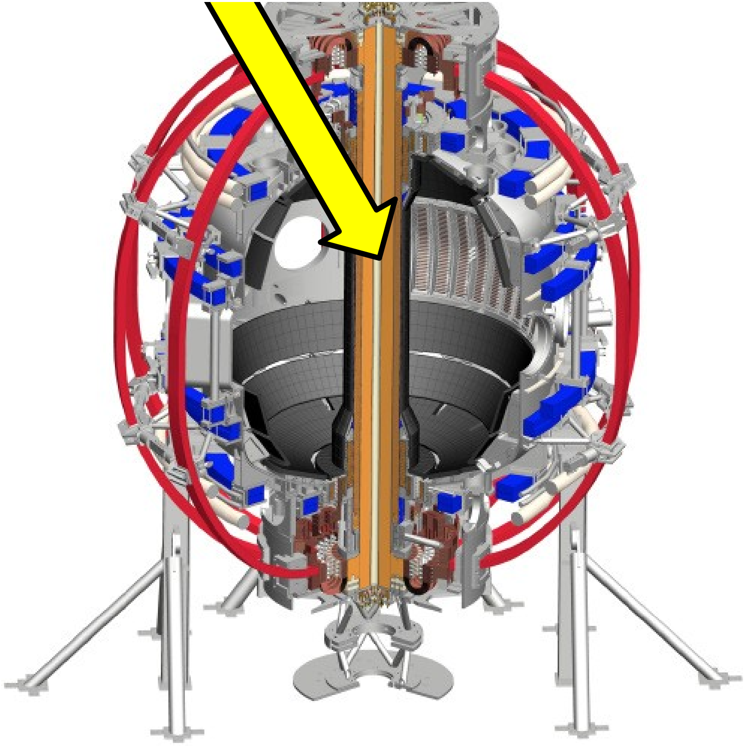


Outline

- Physics Goals, Performance Parameters
- Highlights from Construction Project
- Operational Status
- Research Priorities
- Schedule
- Summary

NSTX-U will access new physics with 2 major new tools:

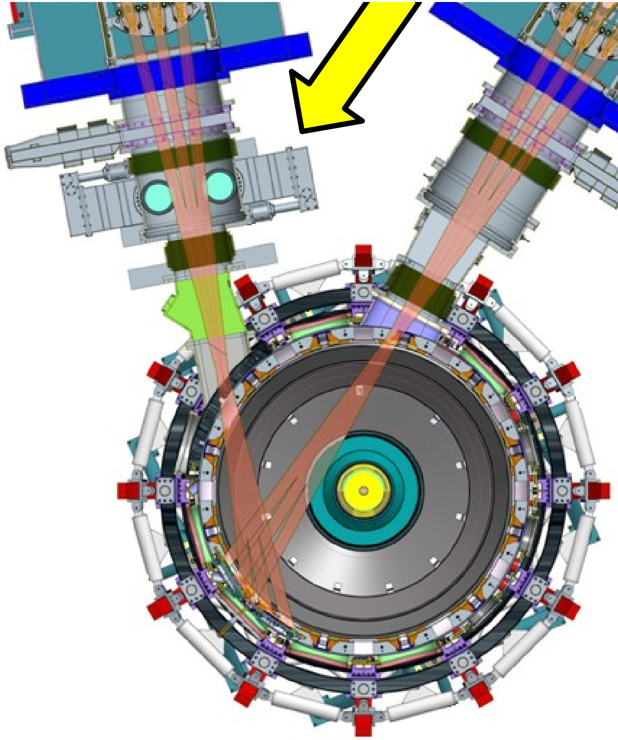
1. New Central Magnet



Higher T, low collisionality at high β

→ Unique regime, study new transport and stability physics

2. Tangential 2nd Neutral Beam



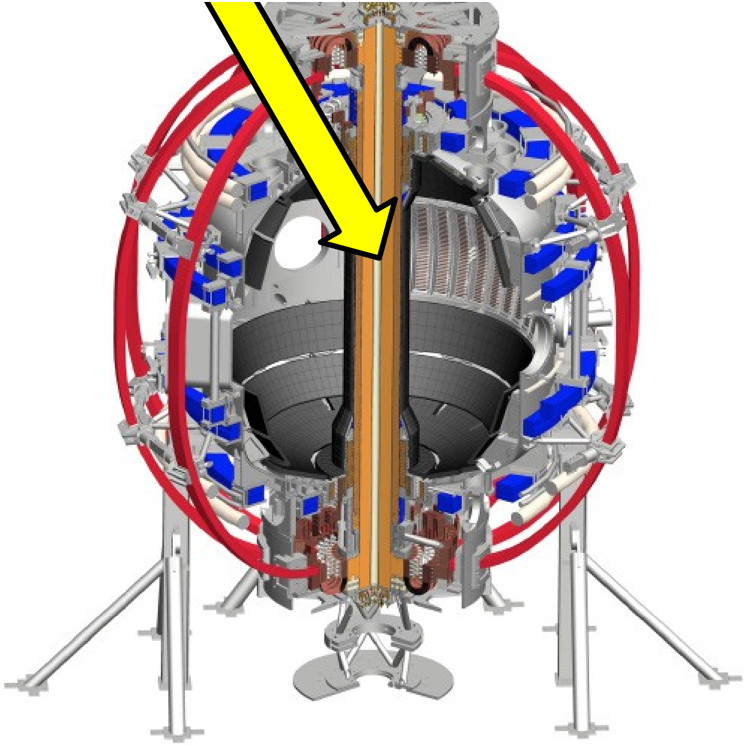
Full non-inductive current drive

→ Not demonstrated in ST at high-β_T

Essential for any future steady-state ST

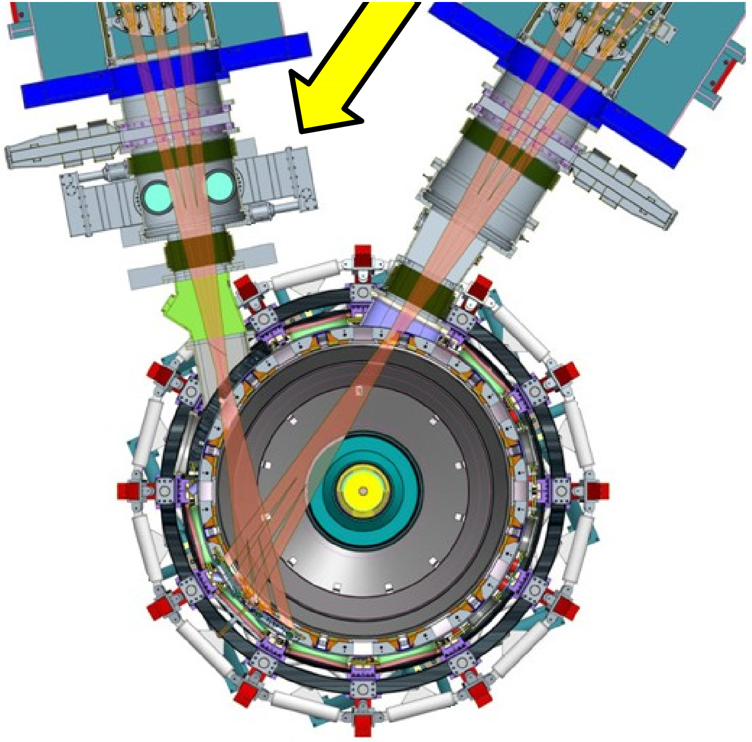
NSTX-U will have major boost in performance

1. New Central Magnet



- ➢2× toroidal field (0.5 → 1T)
- ➢2× plasma current (1 → 2MA)
- ➢5× longer pulse (1 → 5s)

2. Tangential 2nd Neutral Beam



- ➢2× heating power (5 → 10MW)
  - Tangential NBI → 2× current drive efficiency
- ➢4× divertor heat flux (→ ITER levels)
- ➢Up to 10× higher $nT\tau_E$ (~MJ plasmas)

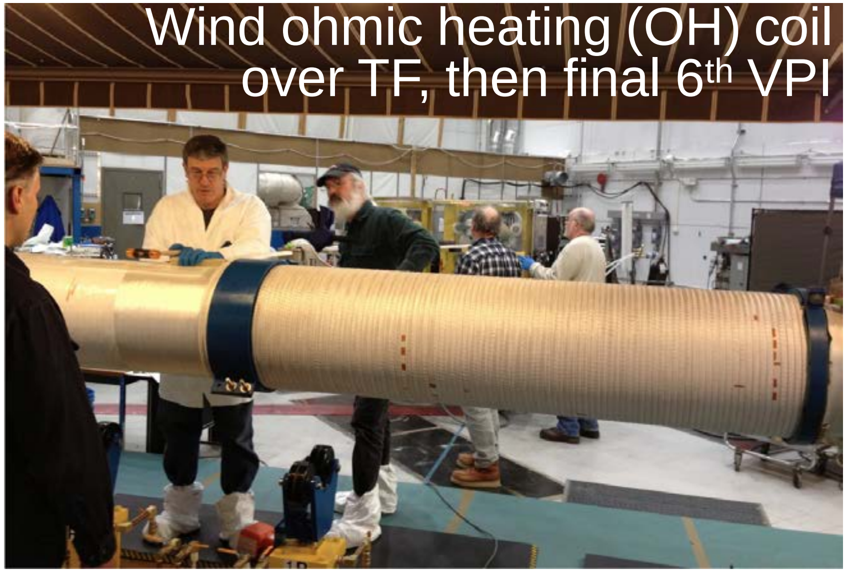
Central magnet construction was complex, multi-stage, multi-year effort

Built 4 toroidal field (TF) quadrants

4 vacuum pressure impregnations (VPI)

Combine quadrants (5th VPI)

Wind ohmic heating (OH) coil over TF, then final 6th VPI



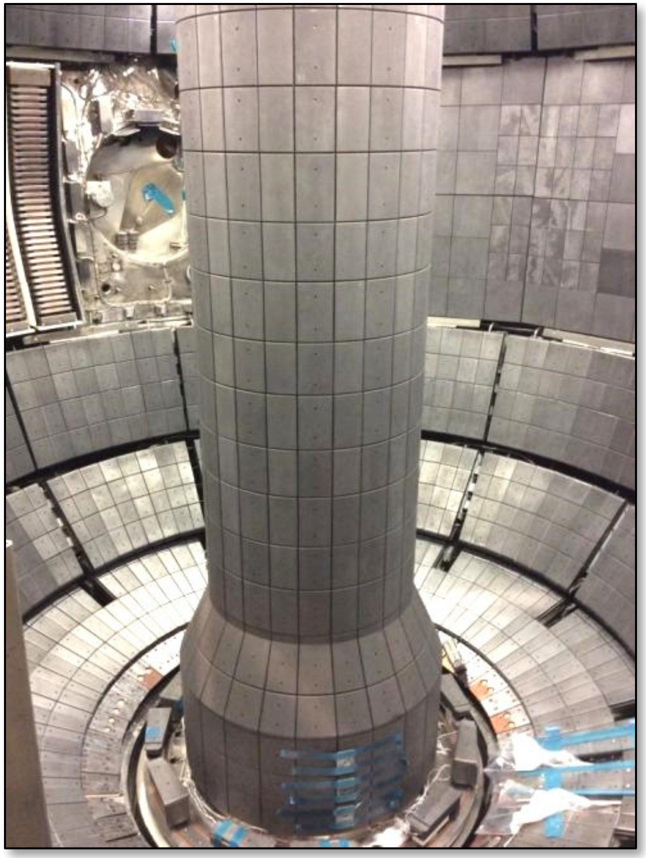
Install vacuum-tight casing over TF + OH bundle

Fabrication and installation of central magnet ultimately successful

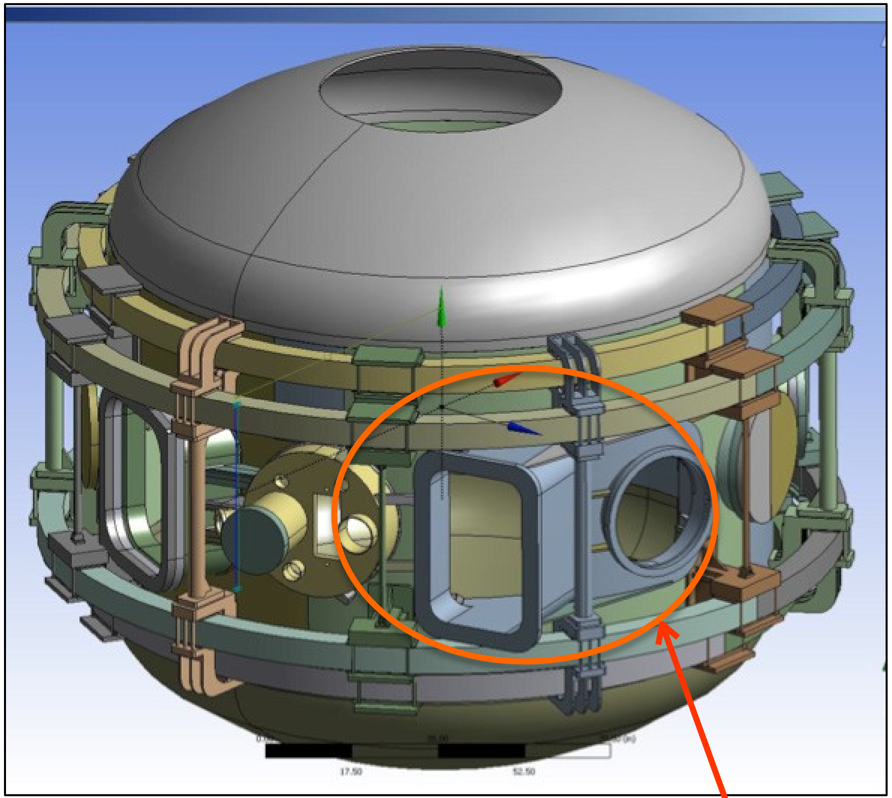
Over the machine

Over shield wall

Inside NSTX-U!

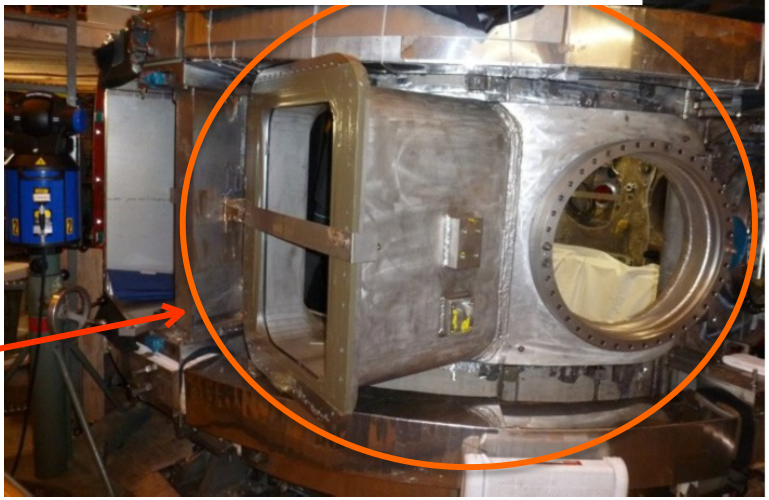


Tangential neutral beam required major vacuum vessel modifications



Interior View of Bay J-K

Exterior View of Bay J-K



JK cap

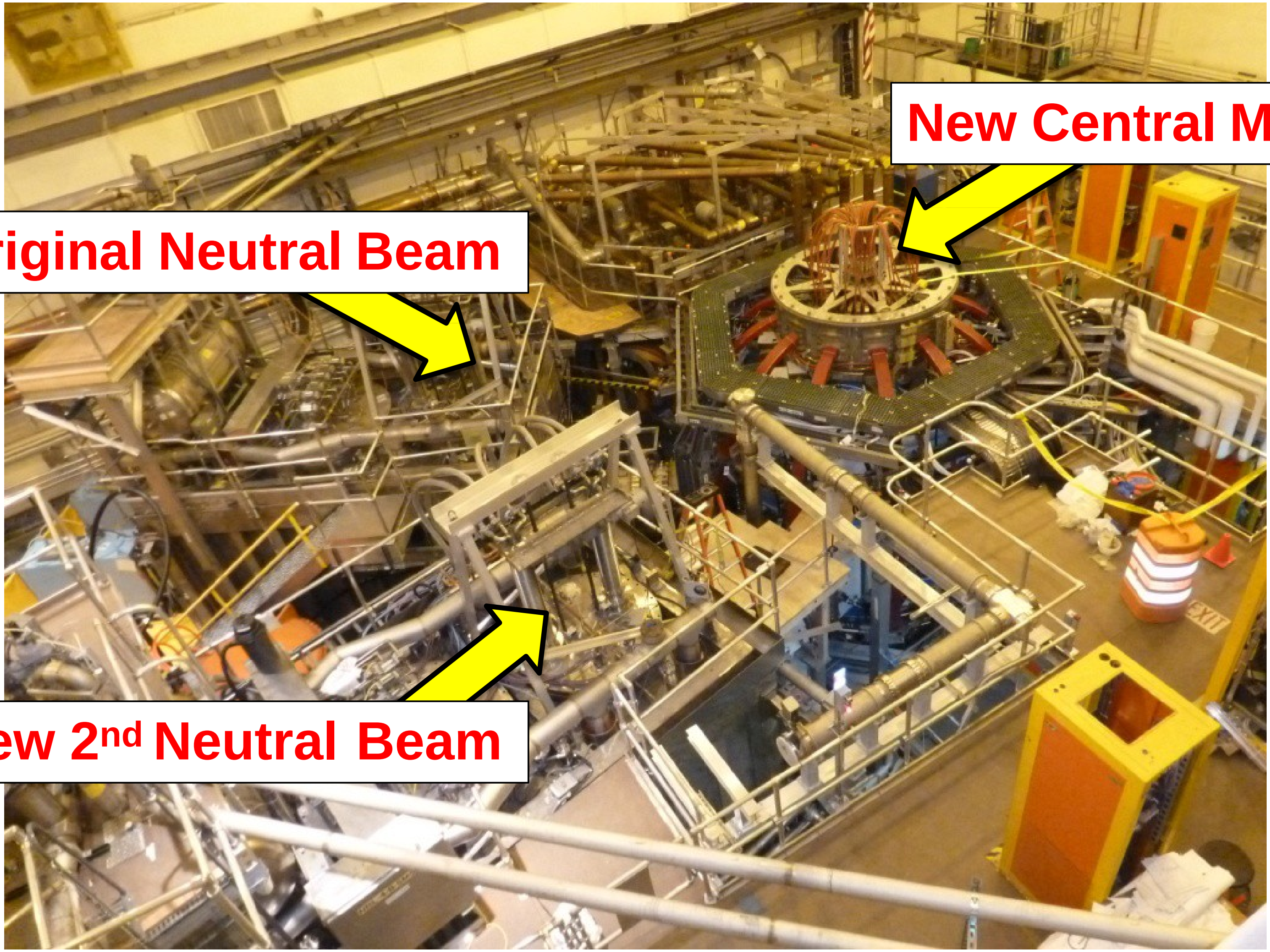
2nd beam (from TFTR DT campaign) required T decontamination, NSTX test-cell re-arrangement

Beam Box being lifted over NSTX

Beam Box placed in its final location and aligned

Beam Box being populated with components

NSTX Upgrade project complete



New Central Magnet

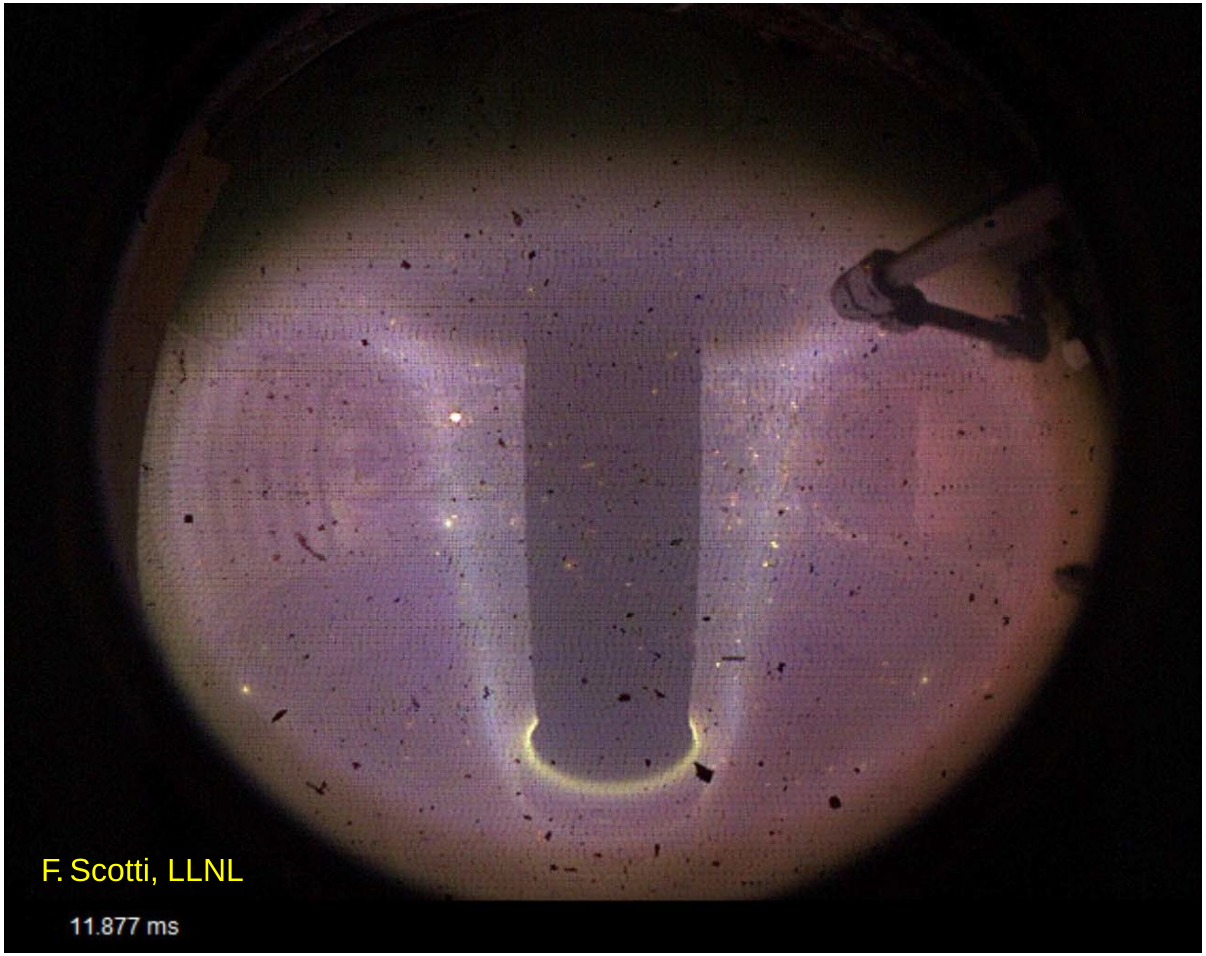
Original Neutral Beam

New 2nd Neutral Beam

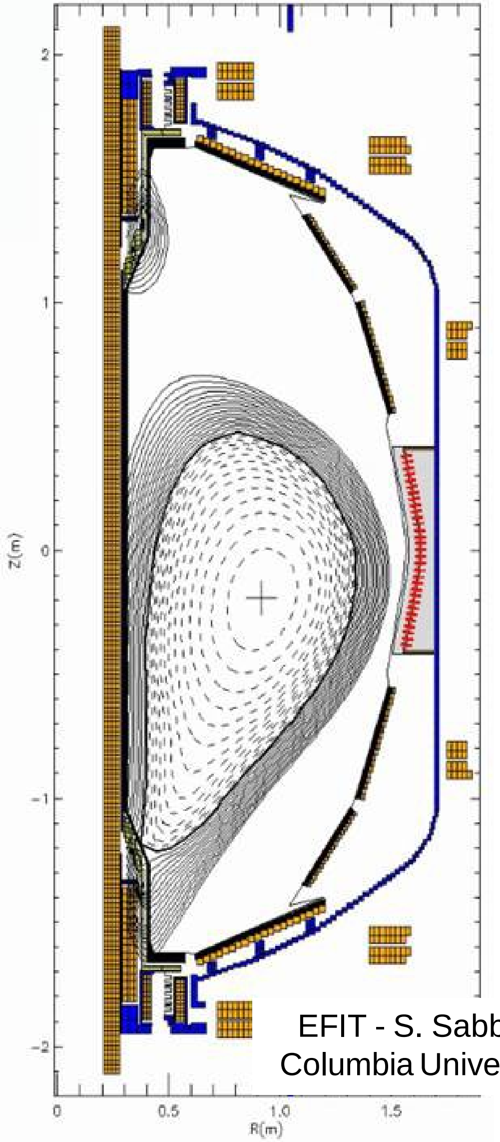
Outline

- Physics Goals, Performance Parameters
- Highlights from Construction Project
- Operational Status
- Research Priorities
- Schedule
- Summary

Achieved 110kA test plasma August 10, 2015



F. Scotti, LLNL



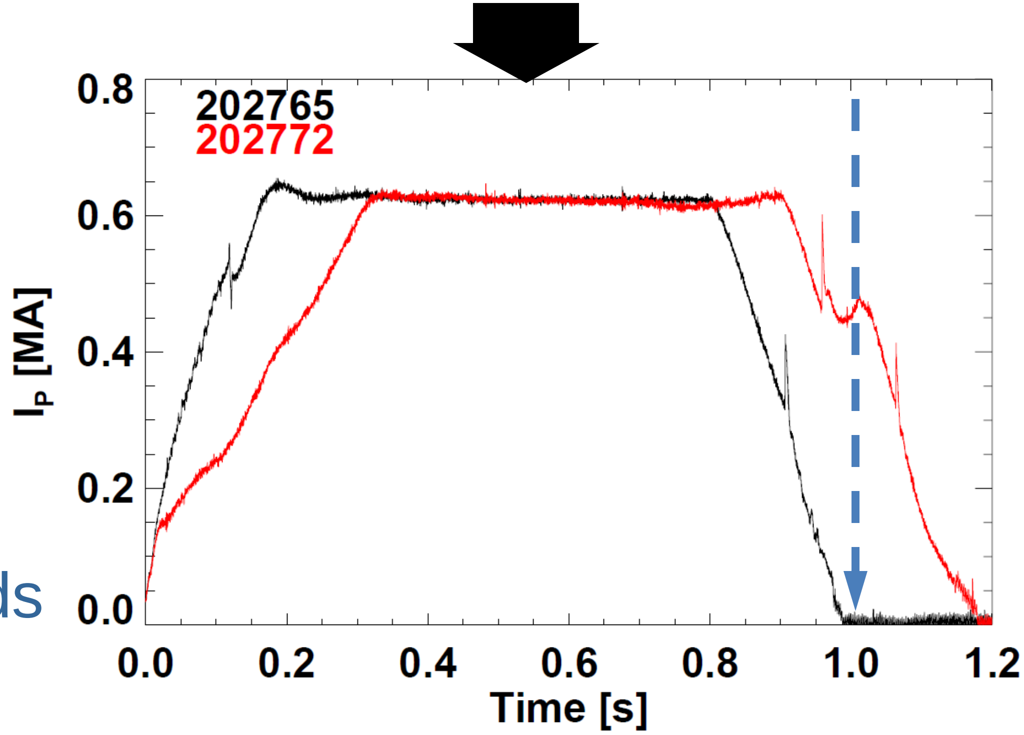
EFIT - S. Sabbagh
Columbia University

NSTX-U is now an operating facility!

Plasma commissioning progressing rapidly thus far

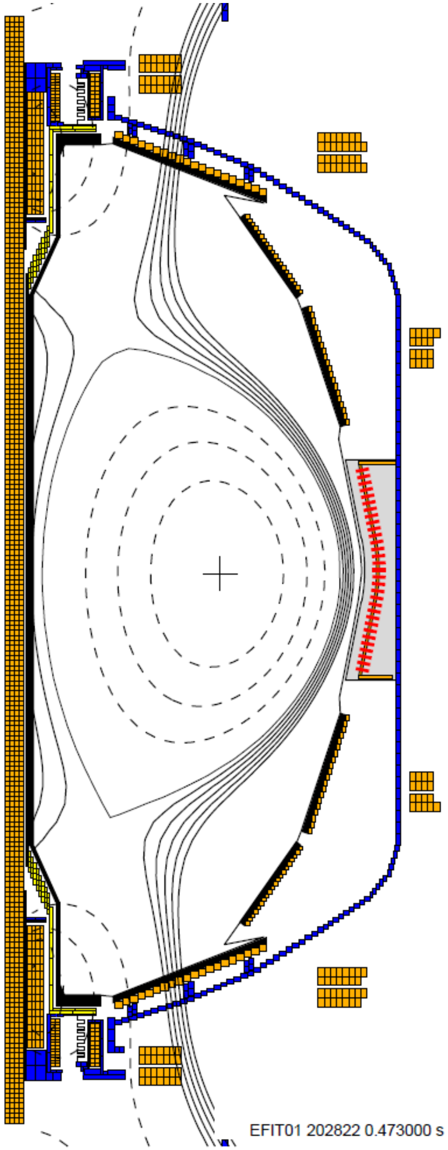
- Completed wall conditioning (bake-out, boronization)
- Began operation in late December
- **Routinely making 0.8-1s plasmas (0.6MA, 0.6T)**

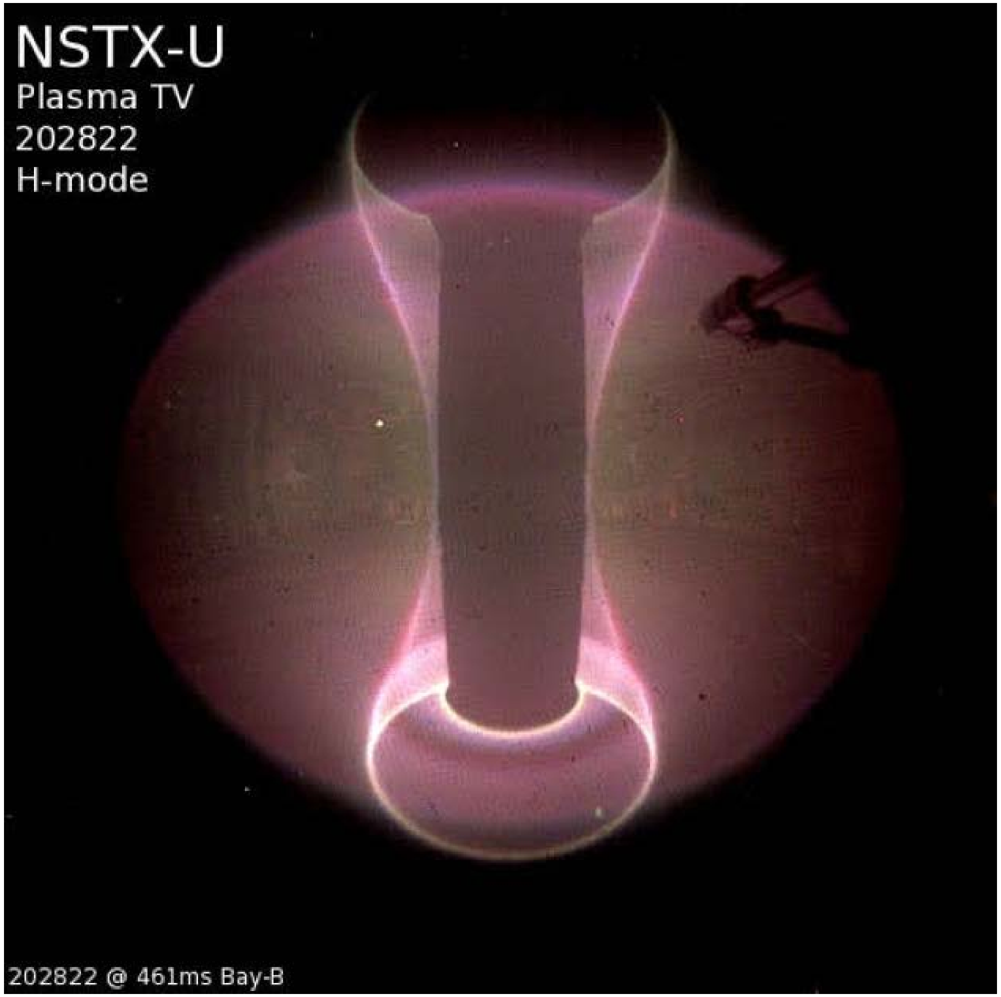
- Optimizing control
  - I_P, gap, elongation κ
- Increasing κ, P_{NBI}
- Next steps:
  - Optimize H-mode / timing
  - Measure/correct error fields
  - Access NSTX-levels of performance, then surpass



B_T already above highest NSTX B_T

Yesterday made first sustained diverted plasmas and accessed first H-modes with 2.5MW NBI





NSTX-U Mission Elements
5 Highest Research Priorities

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  1. Understand energy confinement at high normalized pressure (high β)
  2. Study energetic particle physics prototypical of burning plasmas

- Develop solutions for PMI challenge
  3. Dissipate high edge heat loads using expanded magnetic fields + radiation
  4. Compare performance of solid vs. liquid metal plasma facing components

- Advance ST as possible FNSF / Pilot Plant
  5. Form and sustain plasma current without transformer for steady-state ST

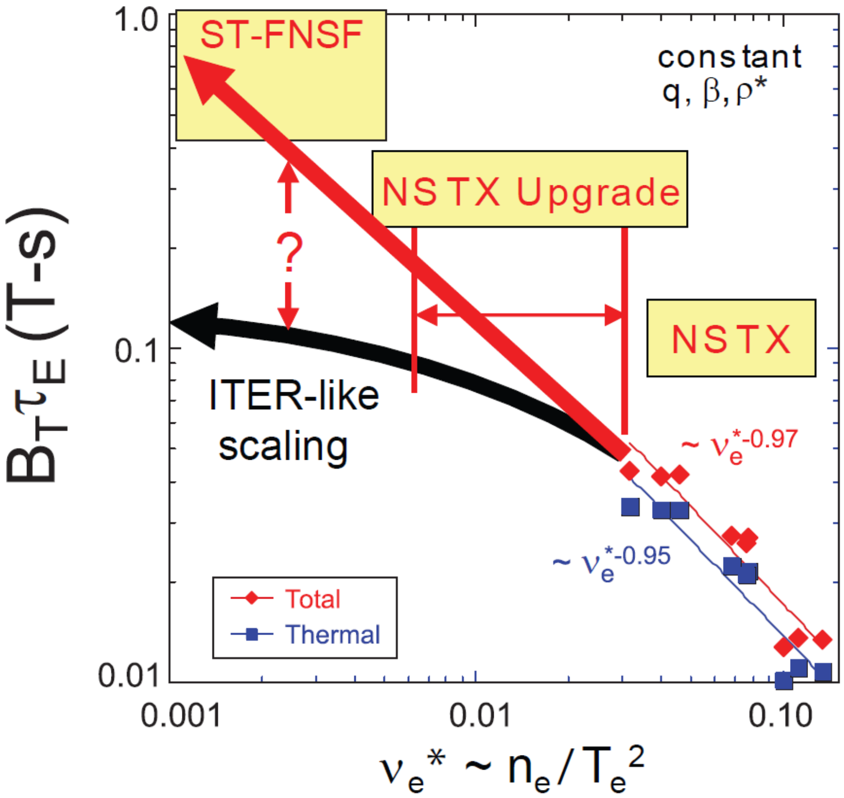
NSTX-U Mission Elements
5 Highest Research Priorities

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  1. Understand energy confinement at high normalized pressure (high β)
  2. Study energetic particle physics prototypical of burning plasmas
- Develop solutions for PMI challenge
  3. Dissipate high edge heat loads using expanded magnetic fields + radiation
  4. Compare performance of solid vs. liquid metal plasma facing components
- Advance ST as possible FNSF / Pilot Plant
  5. Form and sustain plasma current without transformer for steady-state ST

Favorable confinement trend with collisionality and β found in ST experiments

$\tau_{E,\,th} \propto \nu_{*e}^{-0.8}\ \beta^{-0.0}$ **ST scaling observed in NSTX and MAST**

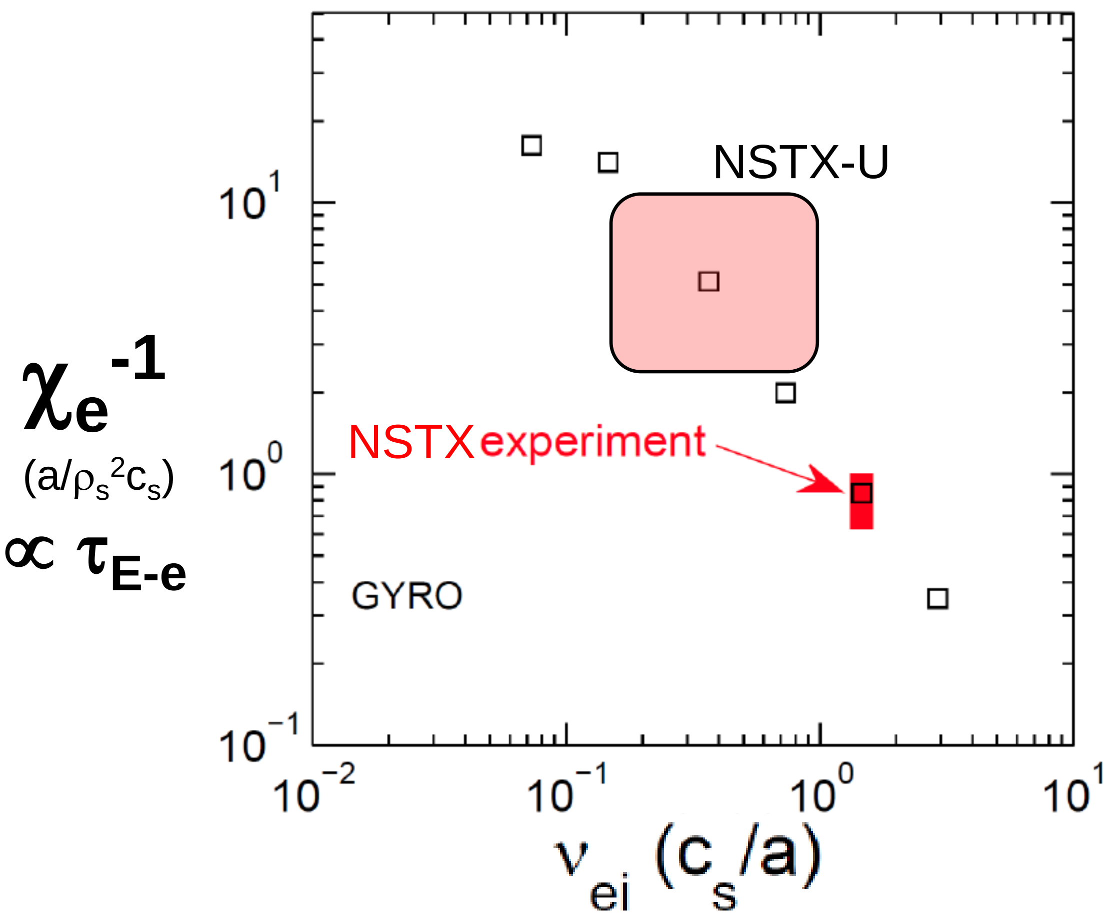
$\tau_{E,\,th} \propto \nu_{*e}^{-0.1}\ \beta^{-0.9}$ **tokamak empirical scaling (ITER 98y,2)**



Promising scaling to ST-FNSF / Pilot, will trend continue on NSTX-U / MAST-U?

Electromagnetic effects may play important role in collisionality scaling of ST confinement

Micro-tearing $\tau_{E\text{-}e}$ vs. ν_{ei} similar to experiment

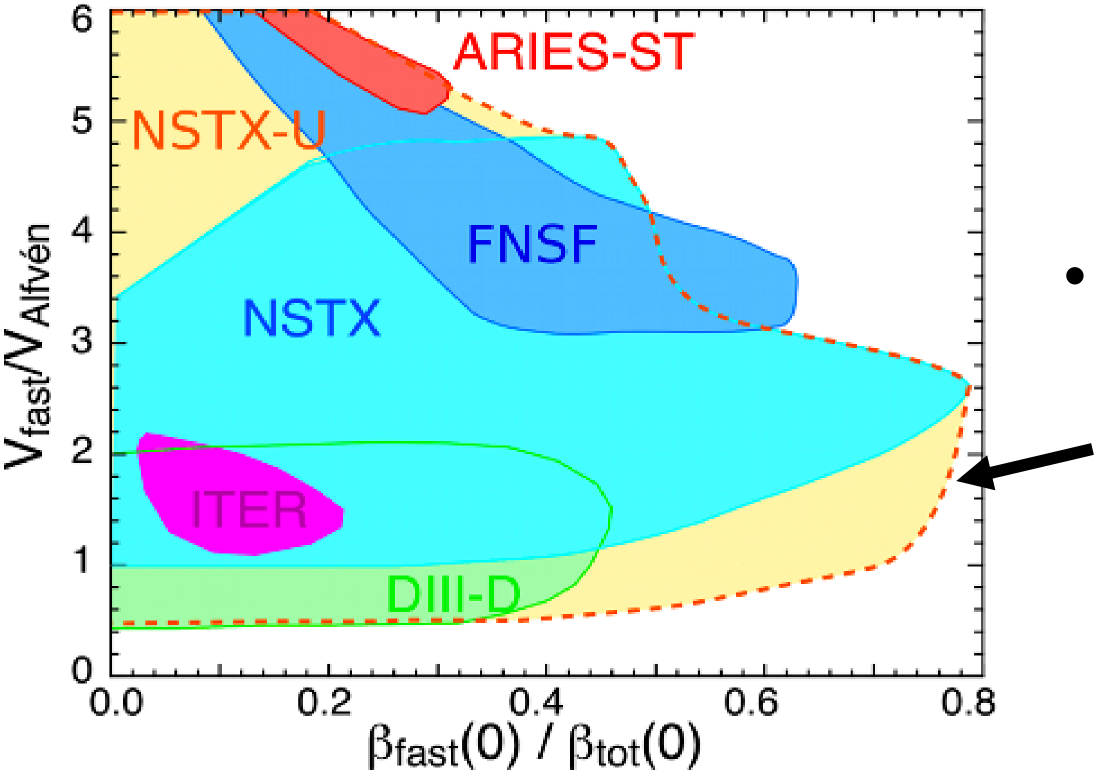


- High β → small-scale overlapping tearing modes → transport from magnetic turbulence
  (GYRO – W. Guttenfelder)
- Other electrostatic turbulence may also have similar ν^* scaling: Dissipative Trapped Electron Mode (GTS - W. Wang)

Will NSTX-U observe confinement improvement at lower collisionality?

NBI-heated STs excellent testbed for α-particle physics

- α-particles couple to Alfvénic modes when $V_\alpha > V_{Alfvén} \sim \beta^{-0.5} C_{sound}$
- $V_{fast} > V_A$ condition easily satisfied in high-β ST with NBI heating

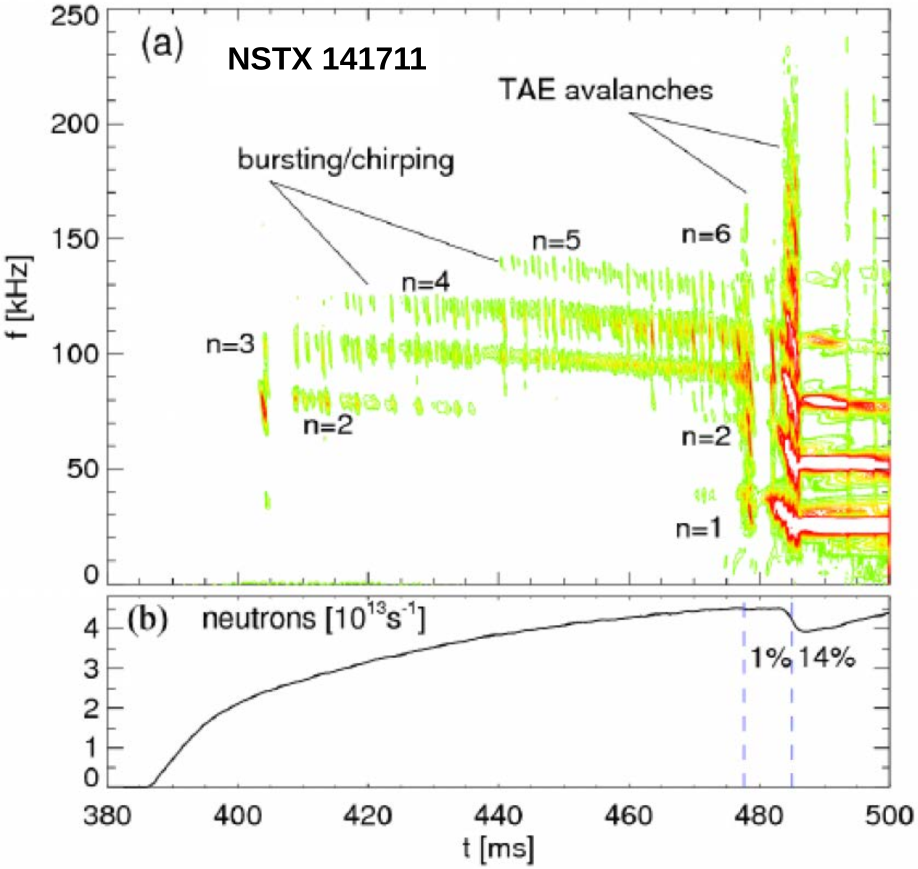


- NSTX-U: large fast-ion dynamic range spanning ST and conventional A
  - **Toroidal field 2× NSTX →** $V_{fast} < V_A$ → stabilize modes
  - **Tangential 2nd NBI →** very flexible fast-ion distribution
    - Vary pitch angle, pressure profile

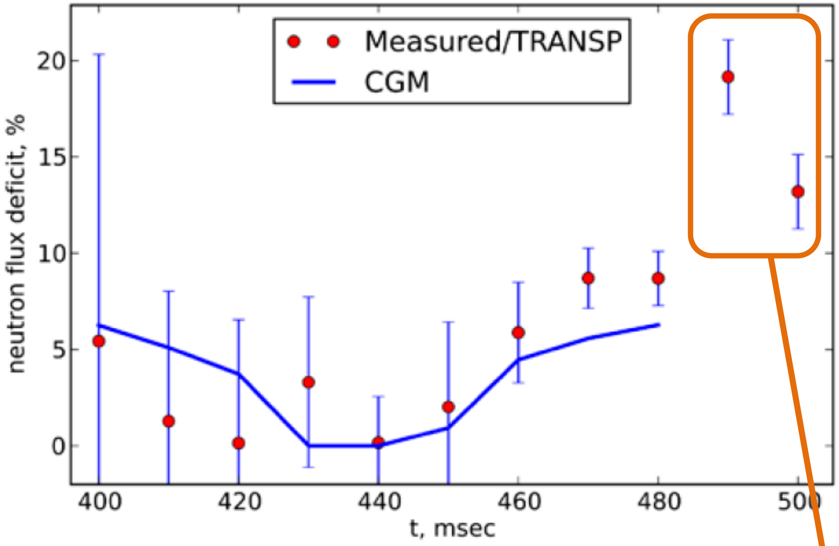
Can we find TAE-quiescent, high-performance regimes in NSTX-U?

"TAE avalanche" can cause energetic particle loss

Uncontrolled α-particle loss could cause reactor first wall damage



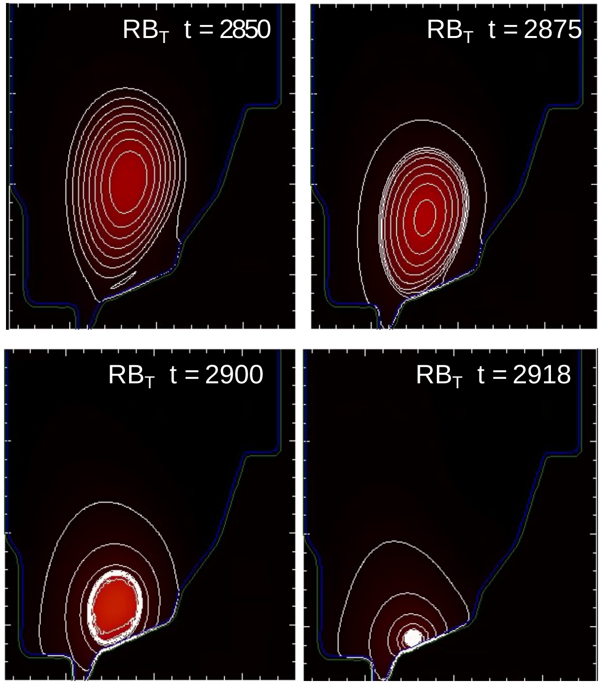
- Quasi-linear "Critical Gradient Model" (CGM) consistent with transport before avalanche



- Working towards fully non-linear multi-mode simulations (e.g. M3D-K) for avalanche phase

NSTX-U aims to play leading role in understanding halo current dynamics, disruption mitigation physics

- Advanced non-linear MHD modelling of vertical displacement events (VDE) + halo currents with M3D-C^1



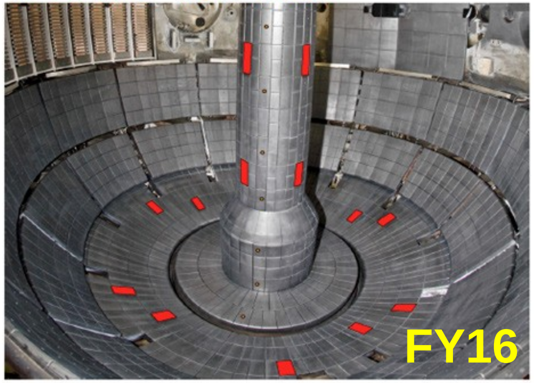
NSTX Discharge 132859

NSTX-U / PPPL Theory Partnership

- Enhance measurements of halo-current dynamics

Planned NSTX-U Base Configuration

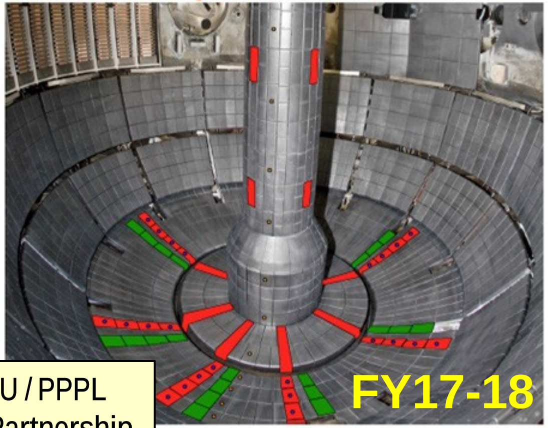
Normal Current Tiles Single Axis B Sensors



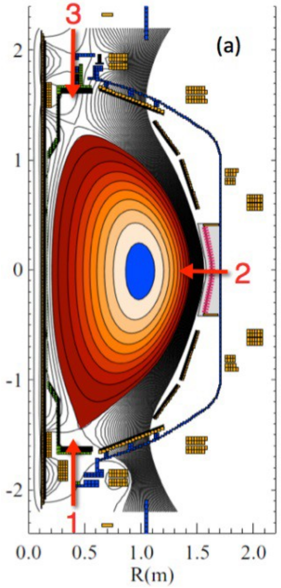
Potential NSTX-U Expanded Configuration

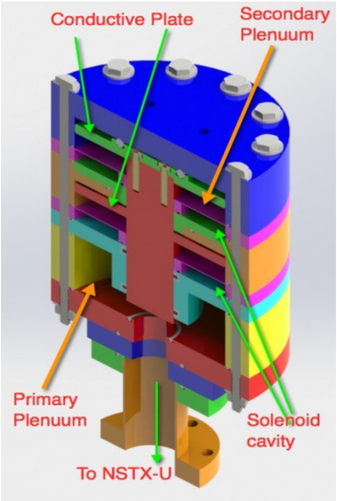
Tangent Current Tiles

Normal Current Tiles Single Axis B Sensors Multi-Axis B sensors



- Test ITER-like Massive Gas Injection (MGI) valves
  - Test poloidal dependence of density assimilation
  - First data expected FY16

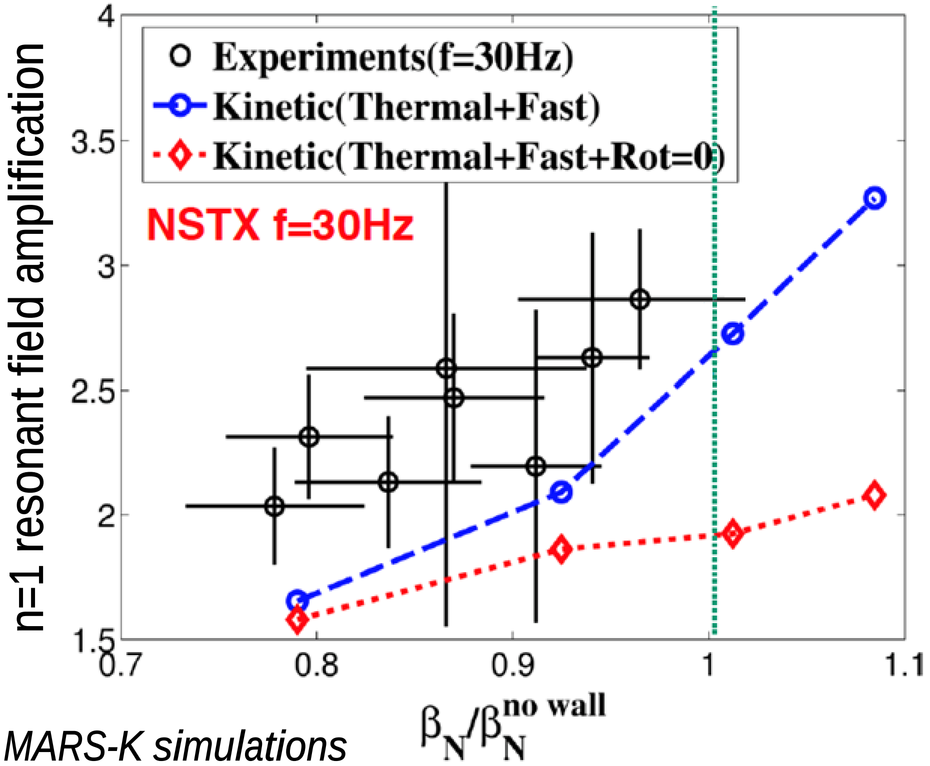




University of Washington

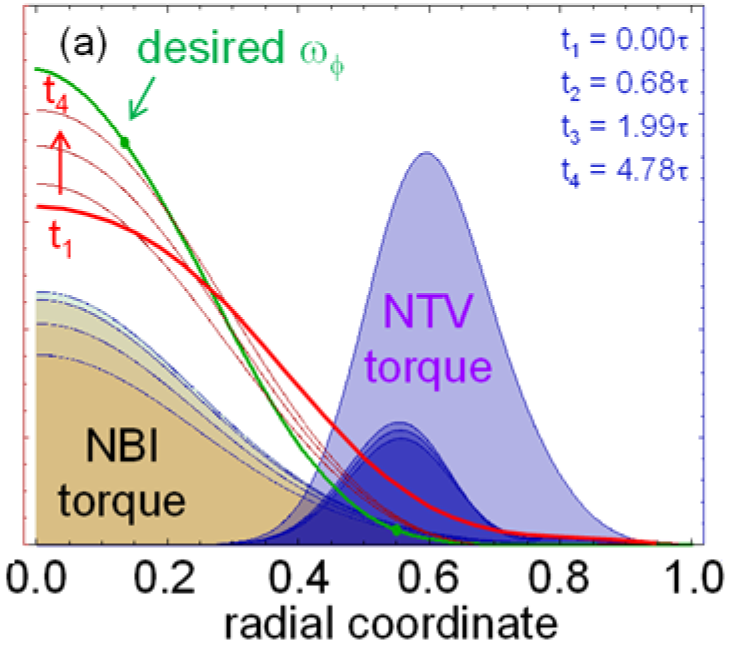
NSTX-U will play key role in understanding stability limits, developing disruption avoidance

- Leaders in understanding kinetic effects in MHD stability
  - NSTX: Drift-kinetic damping, fast-ions, rotation all important



MARS-K simulations

- Developing advanced rotation control to optimize performance
  - Actuators: Beams, 3D fields (NTV)



Princeton, Columbia, PPPL collaboration

NSTX-U Mission Elements
5 Highest Research Priorities

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond

1. Understand energy confinement at high normalized pressure (high β)
2. Study energetic particle physics prototypical of burning plasmas

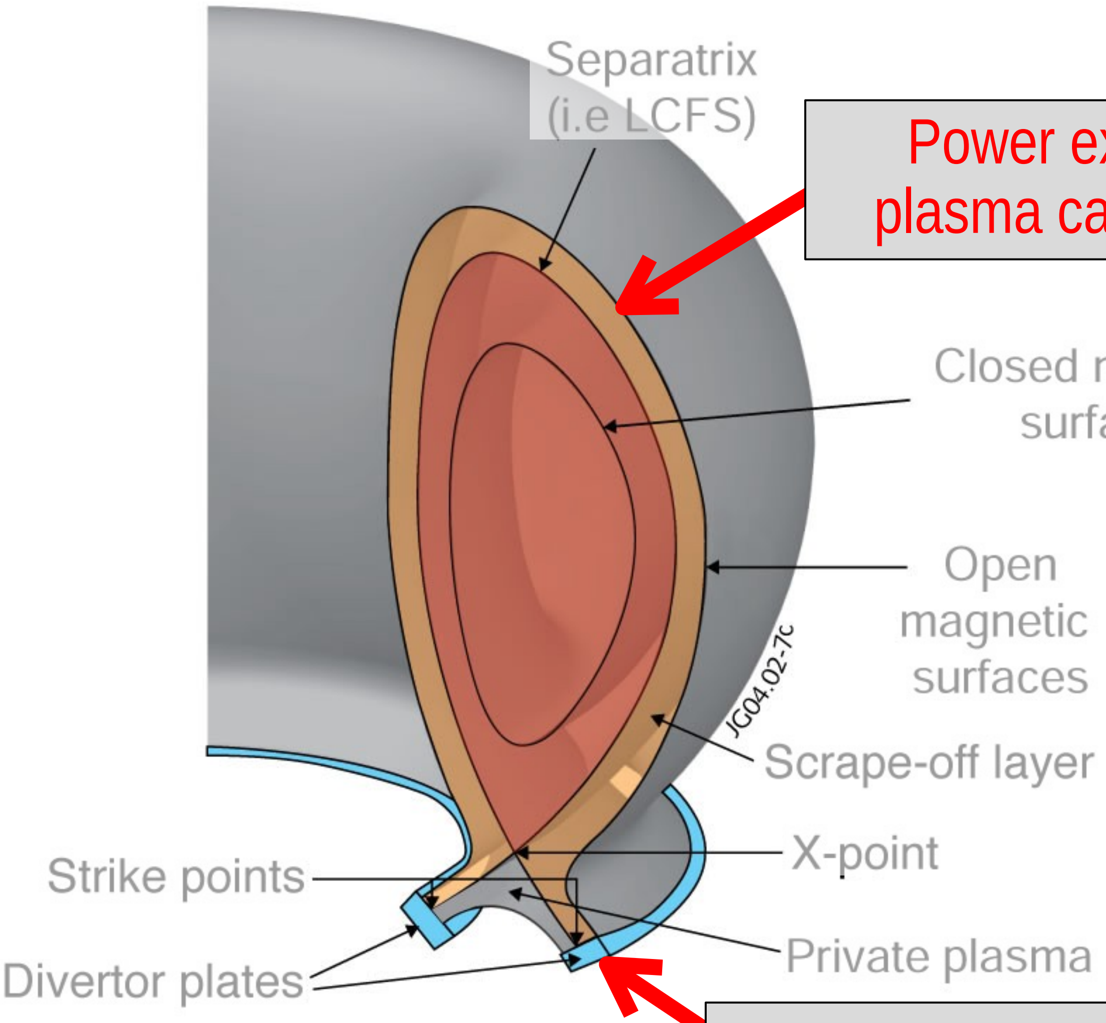
- Develop solutions for PMI challenge

3. Dissipate high edge heat loads using expanded magnetic fields + radiation
4. Compare performance of solid vs. liquid metal plasma facing components

- Advance ST as possible FNSF / Pilot Plant

5. Form and sustain plasma current without transformer for steady-state ST

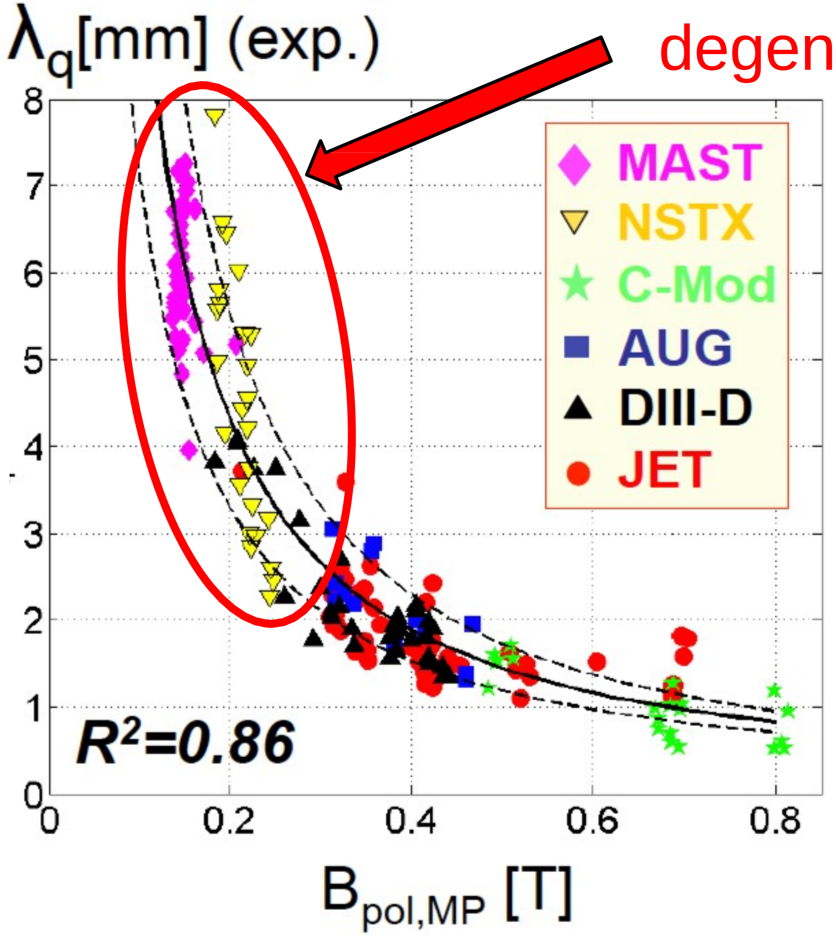
All modern tokamaks / STs use a "divertor" to control where power and particles are exhausted



Power exhaust width outside main plasma can be very narrow (few mm)

Power / particles contact target plates here

Dedicated tokamak + ST experiments found power exhaust width varies as 1 / $B_{poloidal}$



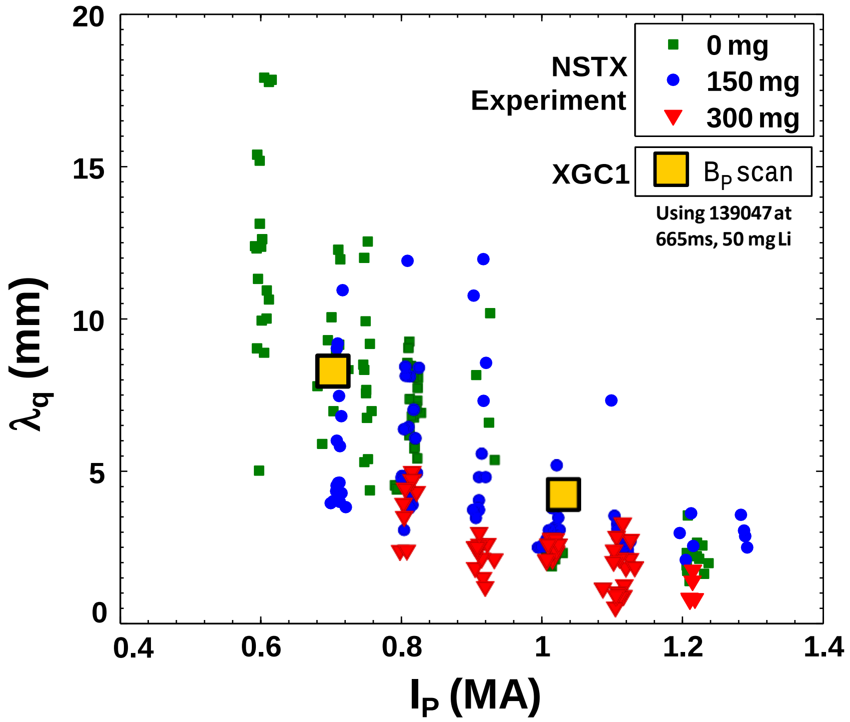
ST data breaks aspect ratio degeneracy of data set

Will 1/$B_{poloidal}$ variation continue at higher I_P? What about detached conditions?

XGC1 simulations aiding in understanding of SOL heat flux width trends in NSTX

- Experiment shows contraction of SOL heat flux width at midplane with I_p as well as influence of Li conditioning

XGC1 w/ collisions → similar trends



Heat flux width determined primarily by neoclassical processes

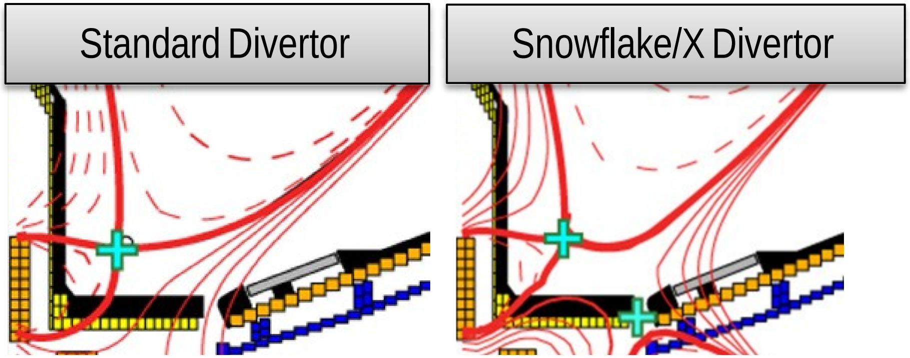
XGC-1:

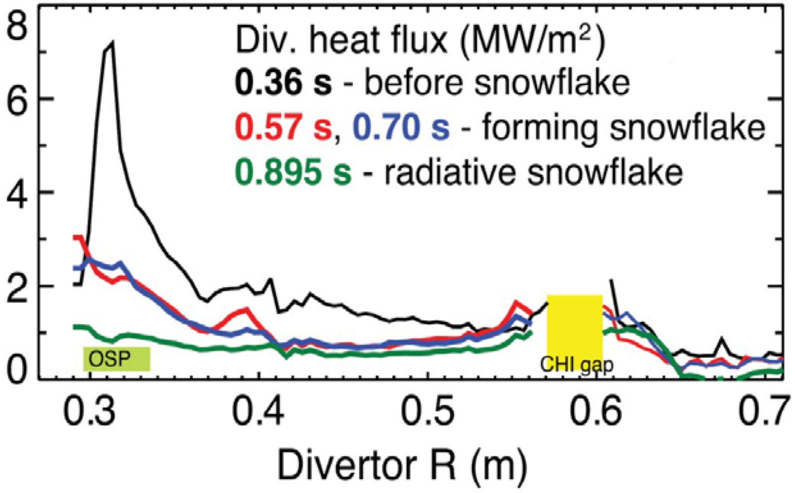
- Full-f, global PIC, kinetic ions, fluid electrons *(kinetic electrons under development)*
- Good candidate for exascale computing initiative

NSTX-U / PPPL Theory Partnership

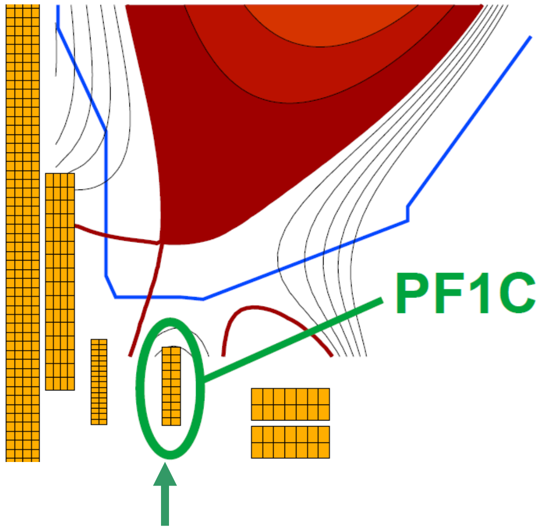
NSTX-U will test ability of radiation and advanced divertors to mitigate very high heat-fluxes

- NSTX: reduced heat flux 2-4 × via radiation (partial detachment)
- Additional null-point in divertor expands field, reduces heat flux





NSTX-U peak heat fluxes will be up to 4-8 × higher than in NSTX

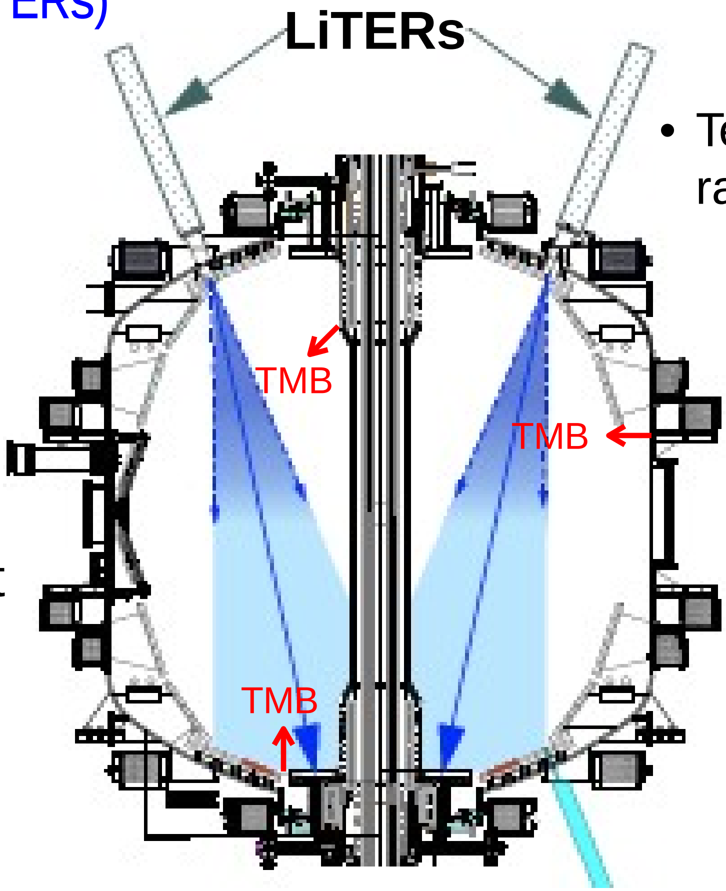


NSTX-U has additional coils for up-down symmetric snowflake/X, improved control

NSTX-U will employ multiple particle control tools to access long-pulse scenarios

2: Lithium Evaporator (LiTERs)

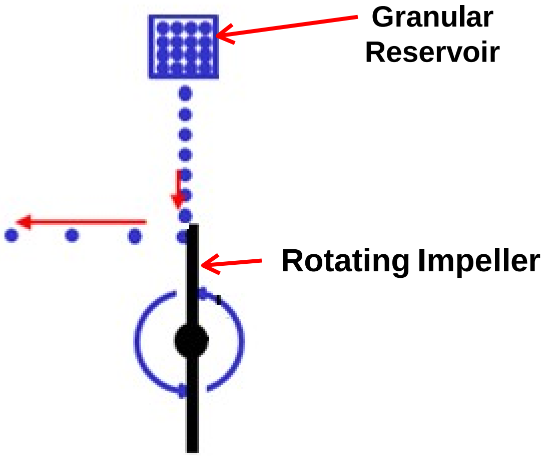
- Pumps deuterium
- Improves confinement
- Often stabilizes ELMs
  → can cause impurity accumulation



1: Boronization (TMB)

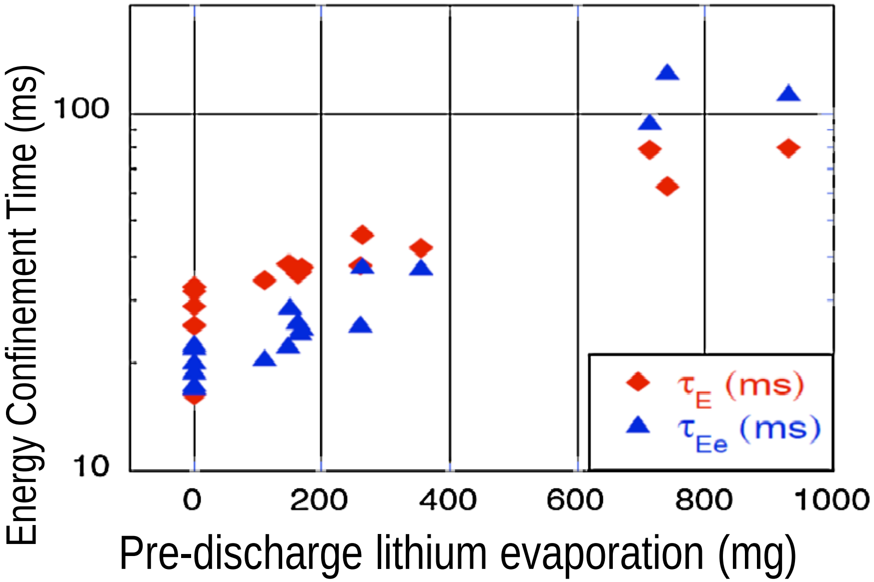
3: Granule injector (GI) for ELM pacing

- Test during FY16 run to trigger rapid ELMs, flush impurities



- Successfully tested on EAST and DIII-D
- NSTX-U will test several granule types: Li, B_4C, C
- $f_{injection}$ ~ up to 500 Hz

Plasma confinement increased continuously with increasing Li coatings in NSTX – what is limit?



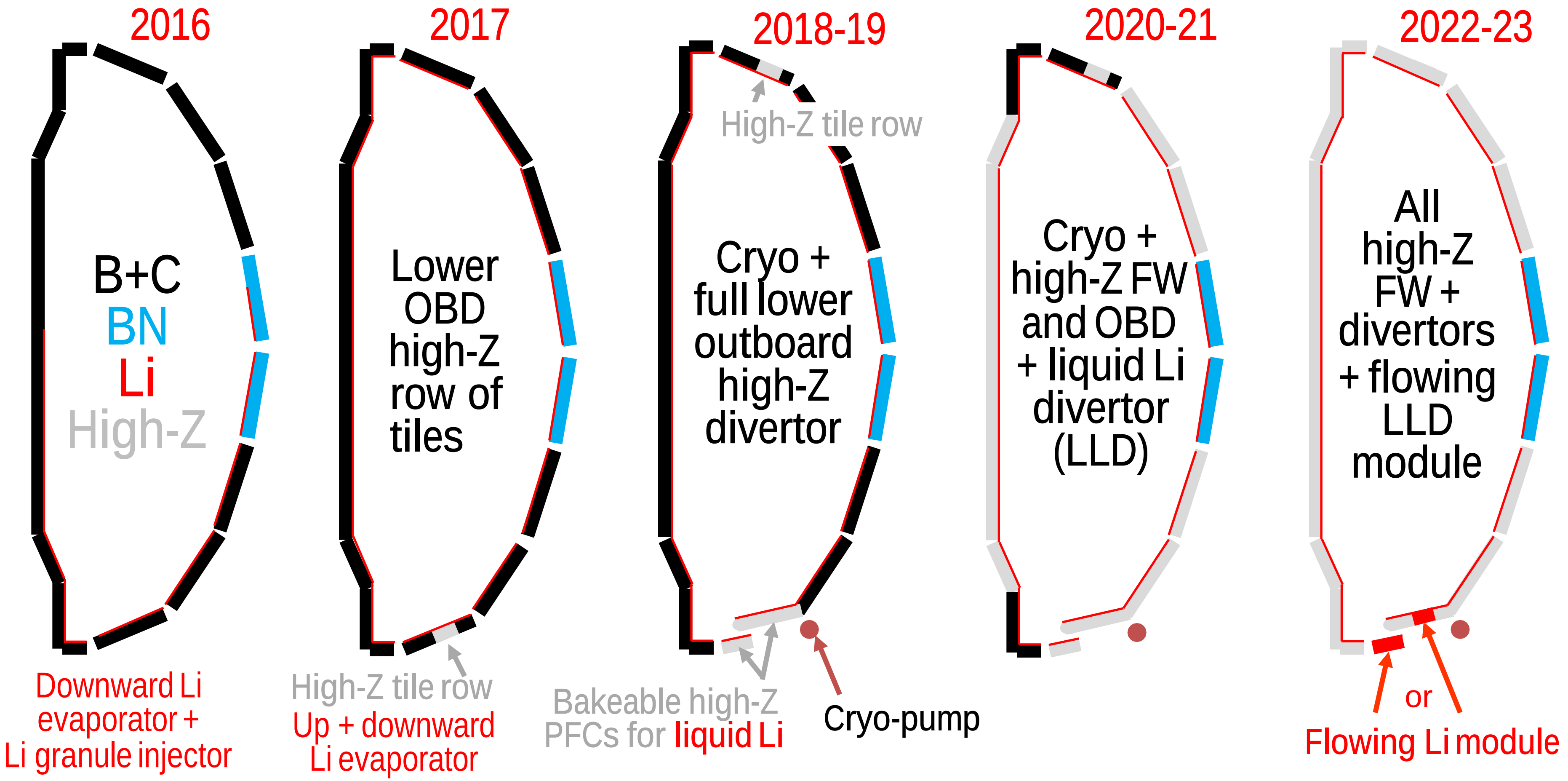
R. Maingi, et al., PRL 107 (2011) 145004

- Global parameters improve
  - H_{98y2} increases ~0.9 → 1.4
  - No core Li accumulation
- High H critical for compact FNSF / Pilot Plants

- NSTX-U will double Li-wall coverage with upward evaporators
- Will further assess contributors to confinement improvement:
  - Lower-recycling / reduced neutral source / higher T_e
  - Edge profile / turbulence changes
  - Influence of (low-Z) impurities in pedestal region

NSTX-U boundary / PFC plan: add divertor cryo-pump, transition to high-Z wall, study flowing liquid metal PFCs

- 5yr goal: Integrate high τ_E and β_T with 100% non-inductive
- 10yr goal: Assess compatibility with high-Z & liquid lithium PFCs



NSTX-U Mission Elements
5 Highest Research Priorities

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  1. Understand energy confinement at high normalized pressure (high β)
  2. Study energetic particle physics prototypical of burning plasmas
- Develop solutions for PMI challenge
  3. Dissipate high edge heat loads using expanded magnetic fields + radiation
  4. Compare performance of solid vs. liquid metal plasma facing components
- Advance ST as possible FNSF / Pilot Plant
  5. Form and sustain plasma current without transformer for steady-state ST

Design studies show ST potentially attractive as Fusion Nuclear Science Facility (FNSF) or Pilot Plant

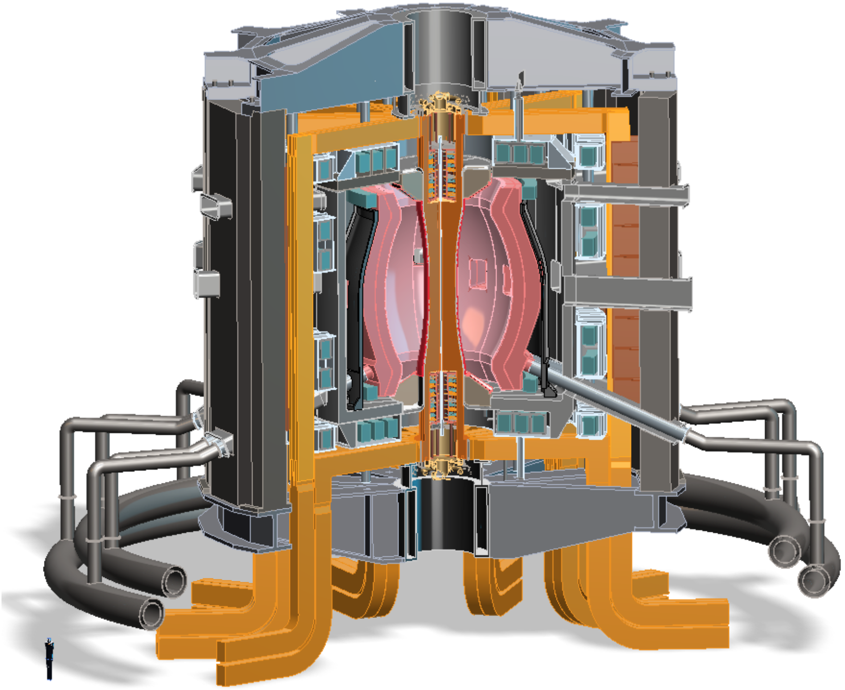
FNSF: Provide neutron fluence for material/component R&D (+ T self-sufficiency?)

Pilot Plant: Electrical self-sufficiency: $Q_{eng} = P_{elec} / P_{consumed} \geq 1$ (+ FNSF mission?)

FNSF with copper TF coils

$A=1.7$, $R_0 = 1.7m$, $\kappa_x = 2.7$

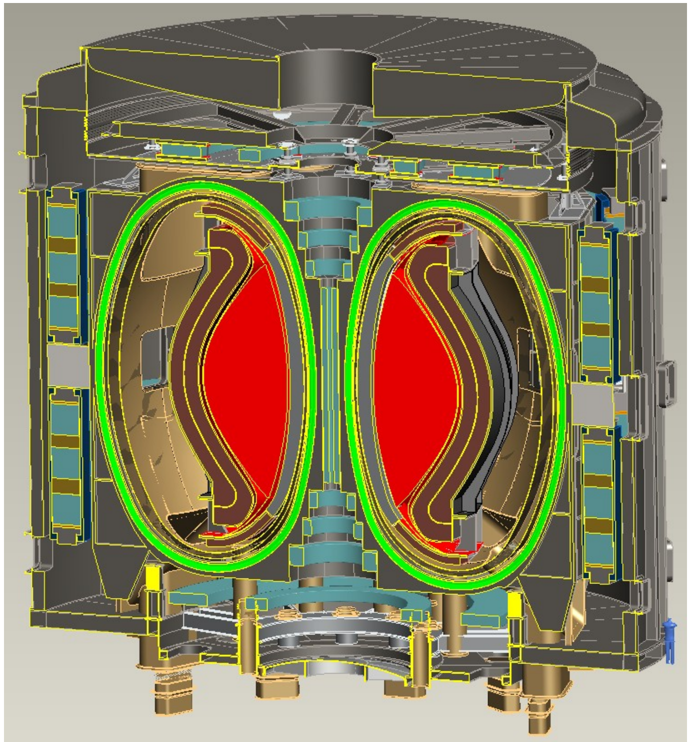
Fluence = $6MWy/m^2$, TBR ~ 1



FNSF / Pilot Plant with HTS TF coils

$A=2$, $R_0 = 3m$, $\kappa_x = 2.5$

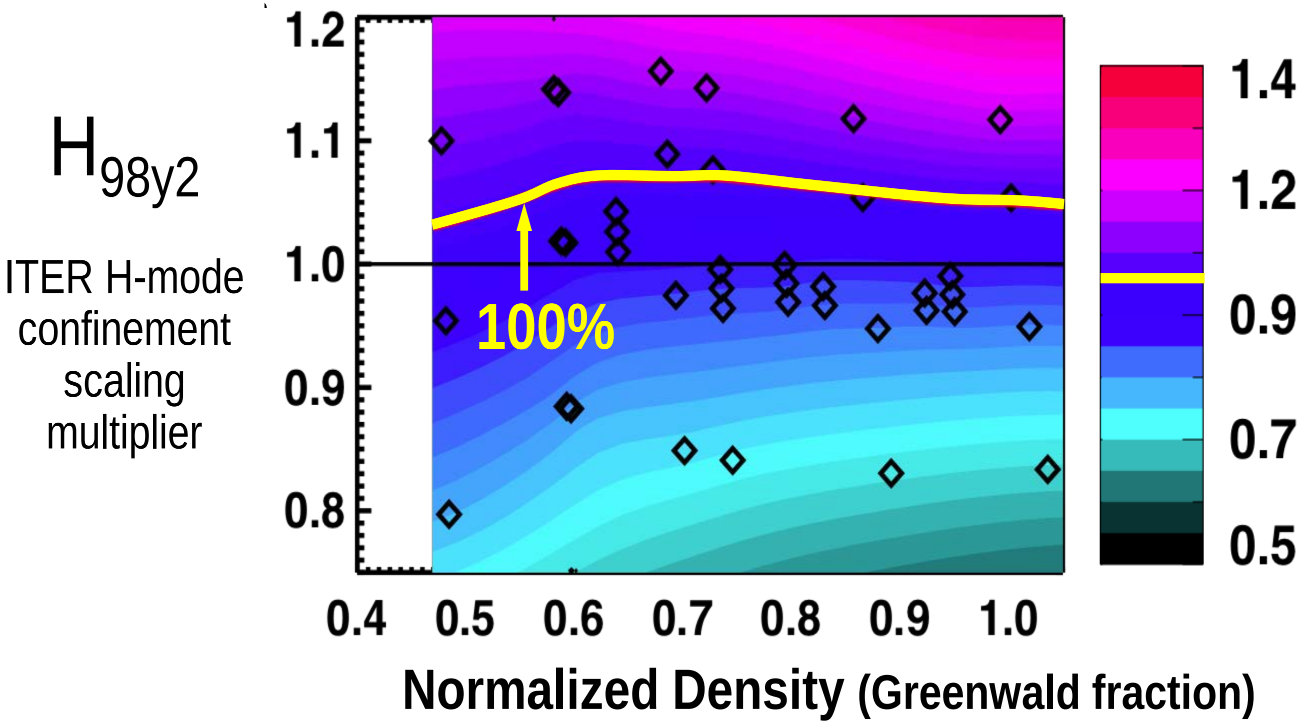
$6MWy/m^2$, TBR ~ 1, Q_{eng} ~ 1



Steady-state operation required for ST/AT FNSF or Pilot Plant

NSTX achieved 70% “transformer-less” current drive

NSTX-U designed to achieve 100% (TRANSP):

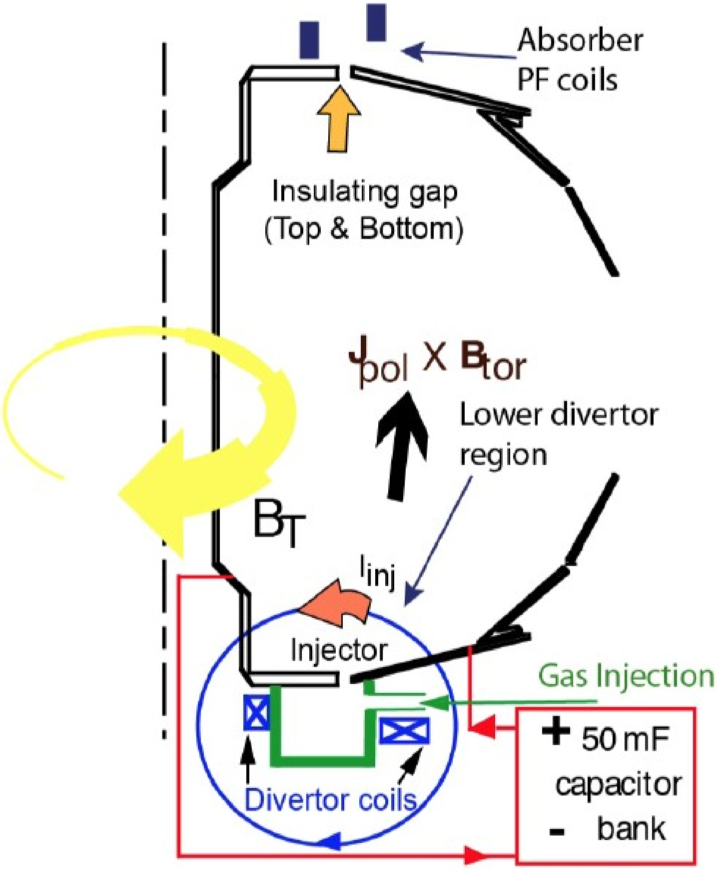


I_P=1 MA, B_T=1.0 T, P_{NBI}=12.6 MW

Will NSTX-U achieve 100% as predicted by simulations?

ST-FNSF may need solenoidless current start-up method
Coaxial Helicity Injection (CHI) effective for current initiation

CHI developed on HIT, HIT-II
Transferred to NSTX / NSTX-U

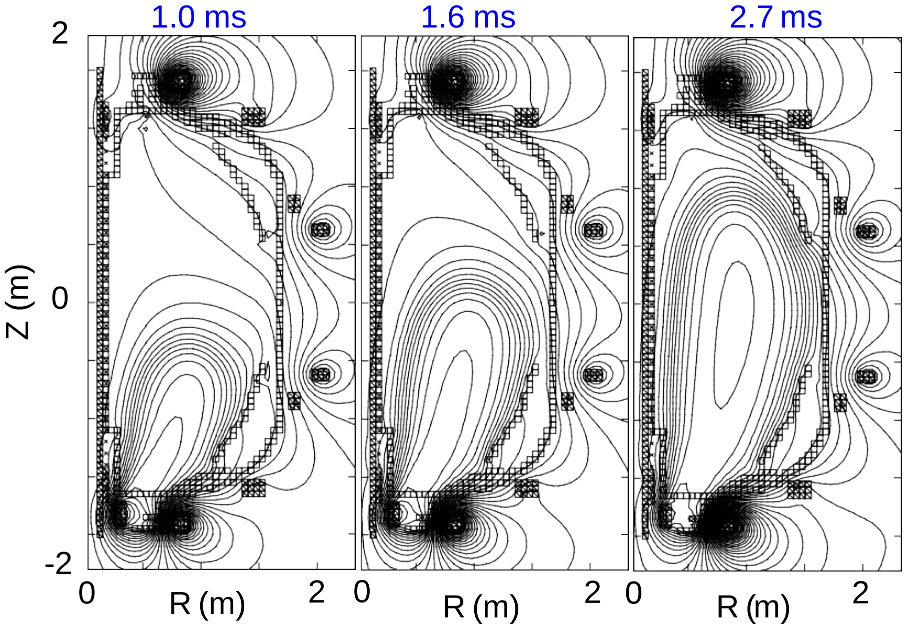


R. Raman et al., PRL 2006

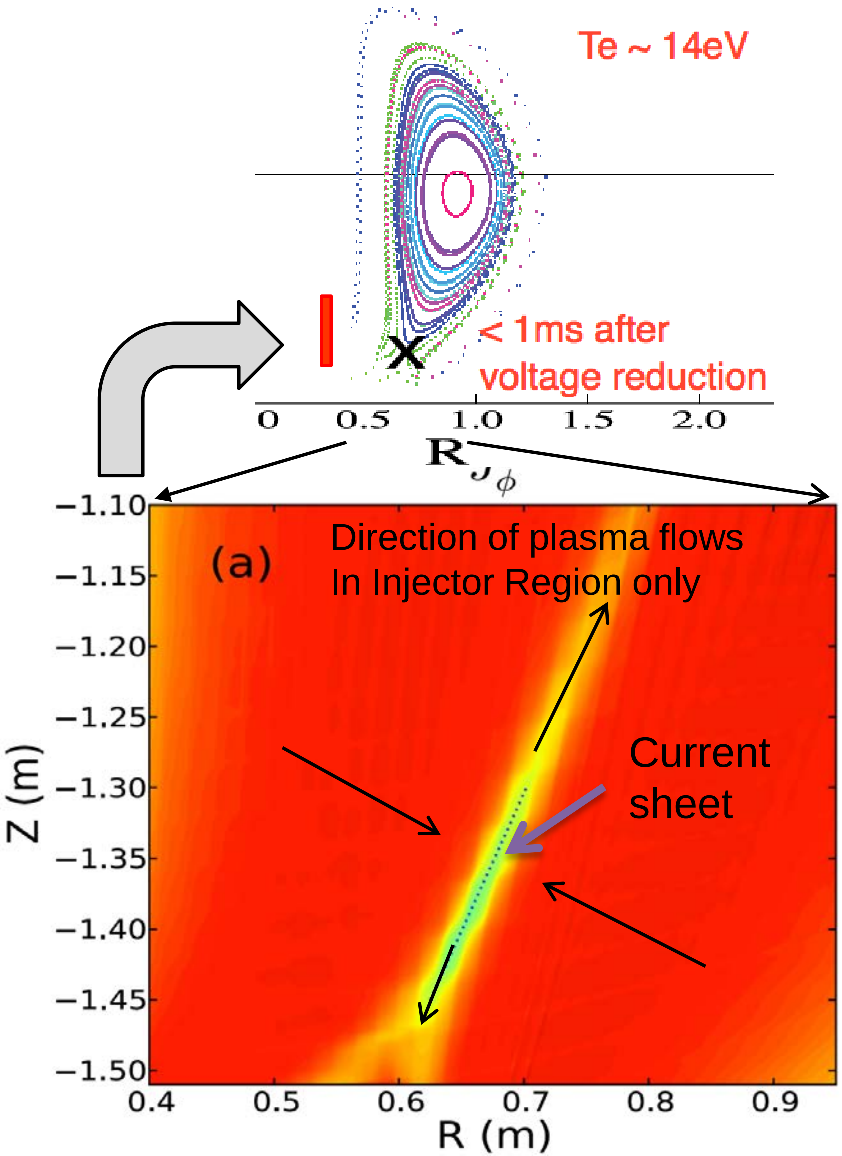
NSTX: 150-200kA closed flux current

NSTX-U: Project 300-400kA

TSC (axisymmetric 2D)
simulation of CHI startup



CHI in NSTX has resemblance to 2D Sweet-Parker reconnection (NIMROD simulations)



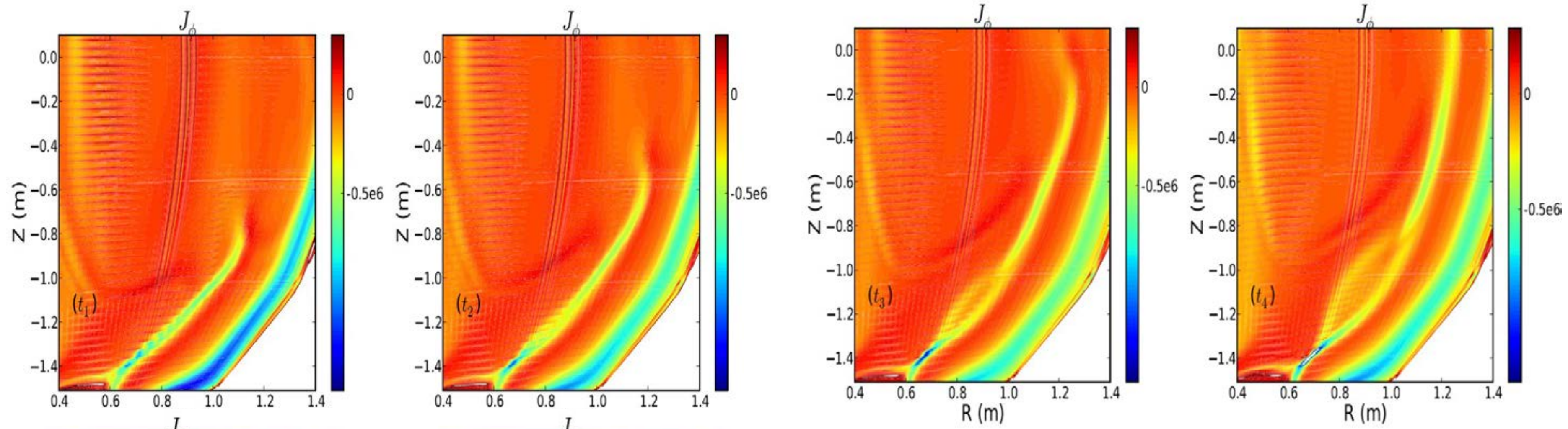
- Toroidal electric field generated in injector region by reduction of injector voltage and current
  - $E_{toroidal}$ × $B_{poloidal}$ drift brings oppositely directed field lines closer and causes reconnection, generating closed flux
- Elongated Sweet-Parker-type current sheet
- n > 0 modes / MHD not strongly impacting 2D reconnection

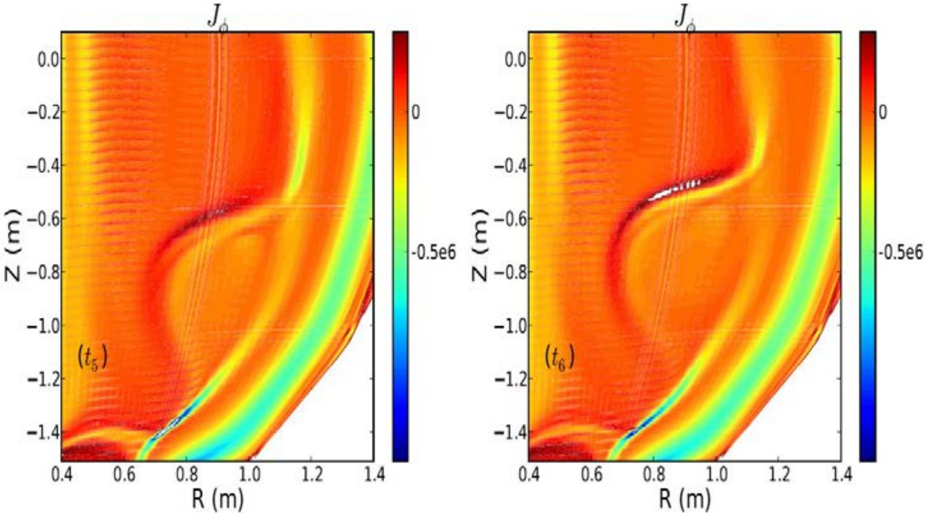
F. Ebrahimi, PoP 2013, PoP 2014

CHI current sheet unstable → plasmoids → merging

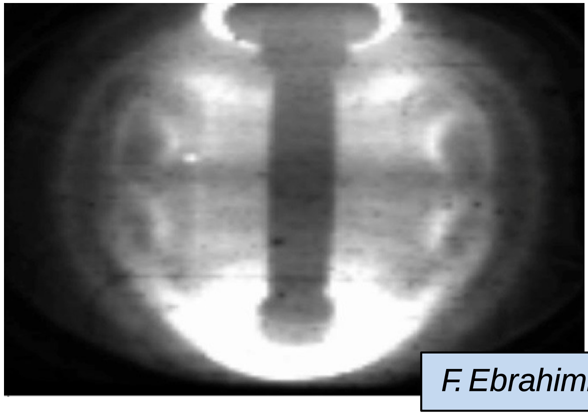
Possible lab observation of plasmoids → contribute to lab-astro

Current sheet shown in the lower half of the device.





Possible plasmoids during NSTX CHI



F. Ebrahimi , PRL 2015

NSTX-U will extend NSTX results, contribute to basic reconnection physics

Outline

- Physics Goals, Performance Parameters
- Highlights from Construction Project
- Operational Status
- Research Priorities
- Schedule
- Summary

Latest run plan schedule for 2016

Goal is to operate 18 run weeks

➔FY16 budgets are favorable enough to support 18 weeks

➔ Want as much data as possible for IAEA synopses/meeting, APS-2016

- **December: 0.5 run weeks (XMP)**
- **January: ~ 2-3 run weeks (XMP, XP), PAC-37**
- **February: ~ 2-3 run weeks (Ar-PS, LITER, LGI, MGI)**
- **March ~ 3 run weeks**
  - **Mid-run assessment in March/April**
- **April – June 9.5 run weeks, complete FY16 run**
- **July: Start outage: install high-k, high-Z tiles, …**
- **Resume operations winter 2017 for FY17: ~16 run weeks**

NSTX-U device performance progression:

- **1st year:** Limit forces to ½ way between NSTX and NSTX-U, and ½ of the design-point heating of any coil
  - Will permit up to ~5 second operation at B_T ~ 0.65T
- **2nd year goal:** Full field and current, coil heating to ¾ of limit
- **3rd year goal:** Full capability

Parameter	**NSTX (Max.)**	**Year 1 NSTX-U Operations**	**Year 2 NSTX-U Operations**	**Year 3 NSTX-U Operations**	**NSTX-U Ultimate Goal**
I_P [MA]	**1.2**	**~1.6**	**2.0**	**2.0**	**2.0**
B_T [T]	**0.55**	**~0.8**	**1.0**	**1.0**	**1.0**
Allowed TF I^2t [MA^2s]	**7.3**	**80**	**120**	**160**	**160**
I_P Flat-Top at max. allowed I^2t, I_P, and B_T [s]	**~0.4**	**~3.5**	**~3**	**5**	**5**

Summary: NSTX-U will make fundamental and world-leading contributions to toroidal fusion science

- Investigate unique high-β, low collisionality regime for understanding transport and stability
- Explore advanced divertors, high-Z and Li walls
- Inform optimal configuration for next-steps
- **FY2016 run campaign is now underway!**

Thank you for your attention!

Backup

Summary of FY2016-18 NSTX-U Research Milestones

- **FY2016**
  - Obtain first data at 60% higher field/current, 2-3× longer pulse:
    - Re-establish sustained low l_i / high-κ operation above no-wall limit
    - Study thermal confinement, pedestal structure, SOL widths
    - Assess current-drive, fast-ion instabilities from new 2nd NBI
- **FY2017**
  - Extend NSTX-U performance to full field, current (1T, 2MA)
    - Assess divertor heat flux mitigation, confinement at full parameters
  - Access full non-inductive, test small current over-drive
  - First data with 2D high-k scattering, prototype high-Z tiles
- **FY2018**
  - Study low-Z and high-Z impurity transport
  - Assess causes of core electron thermal transport
  - Test advanced q profile and rotation profile control
  - Assess CHI plasma current start-up performance

NSTX-U Milestone Schedule for FY2016-18

	FY2016	FY2017	FY2018
Run Weeks: Incremental	**18**	**16** 18	**12** 16
Boundary Science + Particle Control	R16-1 Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}	R17-1 Assess scaling, mitigation of steady-state, transient heat-fluxes w/ advanced divertor operation at high power density R17-2 Assess high-Z divertor PFC performance and impact on operating scenarios	R18-1 Assess impurity sources and edge and core impurity transport IR18-1 Investigation of power and momentum balance for high density and impurity fraction divertor operation
Core Science	R16-2 Assess effects of NBI injection on fast-ion f(v) and NBI-CD profile	R17-3 Assess τ_E and local transport and turbulence at low ν* with full confinement and diagnostic capabilities	IR18-2 Assess role of fast-ion driven instabilities versus micro-turbulence in plasma thermal energy transport Begin ~1 year outage for major facility enhancement(s) sometime during FY2018
Integrated Scenarios	R16-3 Develop physics + operational tools for high-performance: κ, δ, β, EF/RWM	IR17-1 Assess fast-wave SOL losses, core thermal and fast ion interactions at increased field and current R17-4 Develop high-non-inductive fraction NBI H-modes for sustainment and ramp-up	R18-2 Control of current and rotation profiles to improve global stability limits and extend high performance operation R18-3 Assess transient CHI current start-up potential in NSTX-U
FES 3 Facility Joint Research Target (JRT)	C-Mod leads JRT Assess disruption mitigation, initial tests of real-time warning, prediction	DIII-D leads JRT Examine effect of configuration on operating space for dissipative divertors	NSTX-U leads JRT TBD

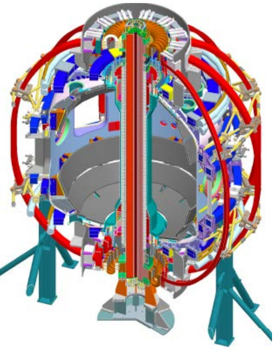
Five Year Facility Enhancement Plan (green – ongoing)

2015: Engineering design for high-Z tiles, Cryo-Pump, NCC, ECH

Fiscal Year:	2015	2016	2017	2018	2019
	Upgrade Outage	1.5 → 2 MA, 1s → 5s			
Run Weeks:		18	16	12-16	10-12

Major enhancements:
- ● Base funding
- ○ +15% incremental

New center-stack

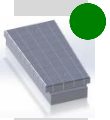


2nd NBI

Boundary Science + Particle Control

Pulse-burst MPTS ●

Boronization ●



● High-Z tile row on lower OBD

Li granule injector ●

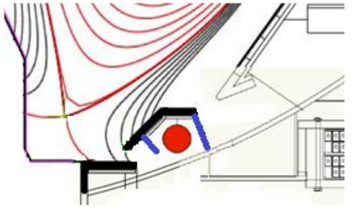
● Upward LiTER

MAPP ●

● Lower divertor cryo-pump

High-Z PFC diagnostics ●

LLD using bakeable ● cryo-baffle



Core Science

Upgraded halo sensors ●

MGI disruption mitigation ●

Laser blow-off ●

42 ch MPTS ●

48 ch BES ●

MSE/LIF ●

High k_θ ●

● Charged fusion product

● 4 coil AE antenna

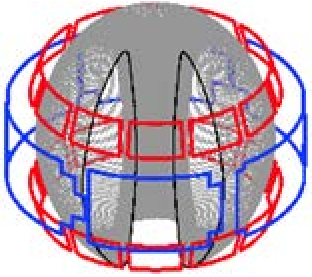
δB diag. - incremental ●

Off-midplane 3D coils (NCC) ○ →

● Enhanced MHD sensors

● DBS, PCI, or other intermediate-k

● Neutron collimator



Integrated Scenarios

Establish control of:

Snowflake ●

FIReTIP ●

Rotation ●

● $\bar{n}_e$

q_{min} ●

●

Divertor P_{rad}

1 MW ECH/EBW ○ →

Upgraded CHI for ~0.5MA ●

0.5-1 MA CHI ●

● HHFW limiter upgrade

● up to 1 MA plasma gun

NSTX-U diagnostics available during first year

MHD/Magnetics/Reconstruction

Magnetics for equilibrium reconstruction
Halo current detectors
High-n and high-frequency Mirnov arrays
Locked-mode detectors
RWM sensors

Profile Diagnostics

MPTS (42 ch, 60 Hz)
T-CHERS: $T_i(R)$, $V_\phi(r)$, $n_C(R)$, $n_{Li}(R)$, (51 ch)
P-CHERS: $V_\theta(r)$ (71 ch)
MSE-CIF (18 ch)
MSE-LIF (20 ch)
ME-SXR (40 ch)
Midplane tangential bolometer array (16 ch)

Turbulence/Modes Diagnostics

Poloidal FIR high-k scattering (installed in 2016)
Beam Emission Spectroscopy (48 ch)
Microwave Reflectometer,
Microwave Interferometer
Ultra-soft x-ray arrays – multi-color

Energetic Particle Diagnostics

Fast Ion D_α profile measurement (perp + tang)
Solid-State neutral particle analyzer
Fast lost-ion probe (energy/pitch angle resolving)
Neutron measurements
Charged Fusion Product

New capability,
Enhanced capability

Edge Divertor Physics

Gas-puff Imaging (500kHz)
Langmuir probe array
Edge Rotation Diagnostics (T_i, V_ϕ, V_{pol})
1-D CCD H_α cameras (divertor, midplane)
2-D divertor fast visible camera
Metal foil divertor bolometer
AXUV-based Divertor Bolometer
IR cameras (30Hz) (3)
Fast IR camera (two color)
Tile temperature thermocouple array
Divertor fast eroding thermocouple
Dust detector
Edge Deposition Monitors
Scrape-off layer reflectometer
Edge neutral pressure gauges
Material Analysis and Particle Probe
Divertor VUV Spectrometer

Plasma Monitoring

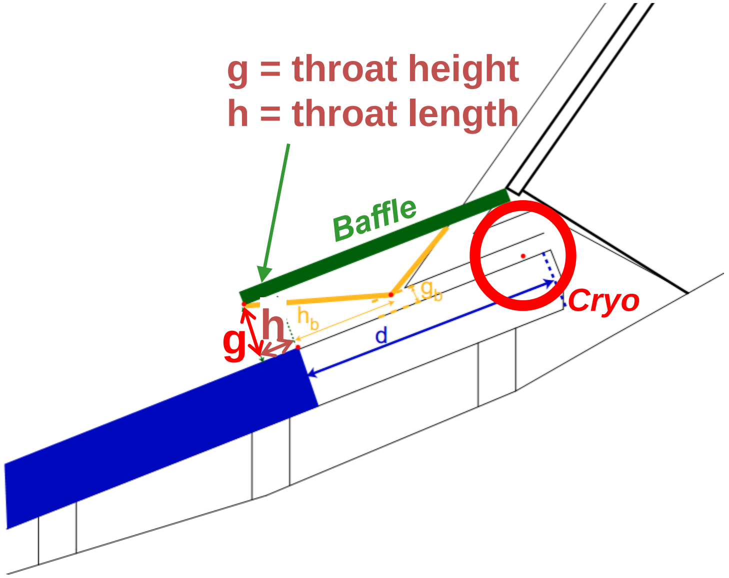
FIReTIP interferometer
Fast visible cameras
Visible bremsstrahlung radiometer
Visible and UV survey spectrometers
VUV transmission grating spectrometer
Visible filterscopes (hydrogen & impurity lines)
Wall coupon analysis

Backup - Facility Enhancements

Cryopump Physics Design Done in Collaboration with ORNL

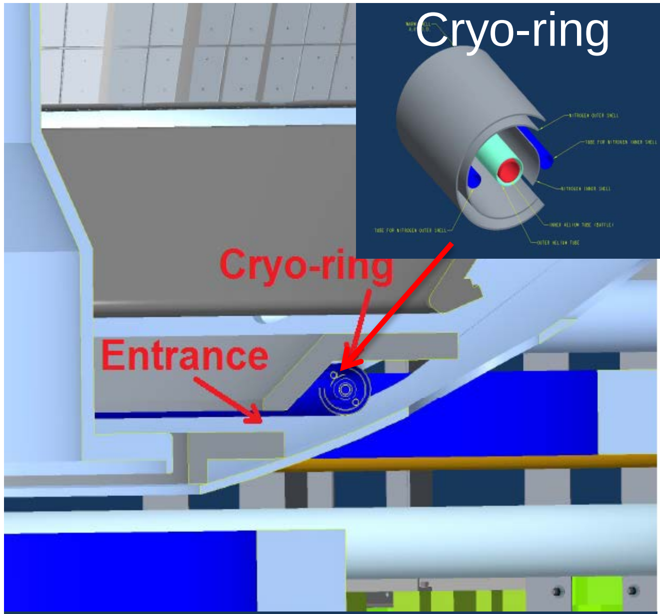
J. Canik, ORNL

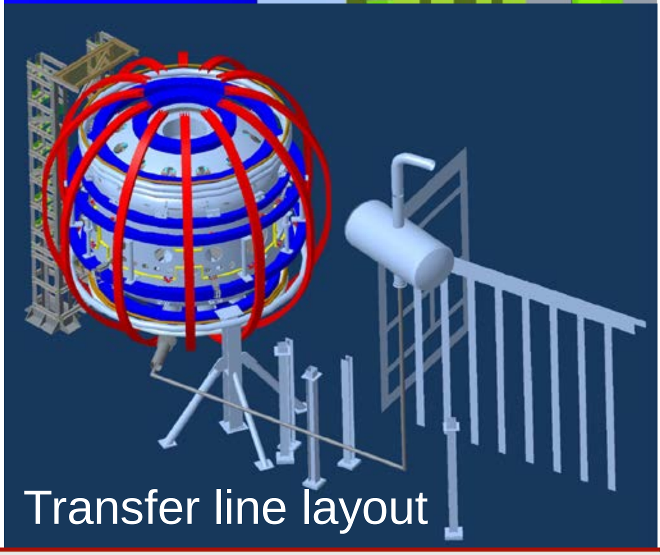
- Initial designs used semi-analytic models to determine pump geometry.
  - – Conclusion on optimum geometry:
    - duct height h~2.5 cm,
    - length h~2 cm,
    - Radius of 0.72 m.
  - – Allows pressures>1 mT over a range of plasma shapes and SoL widths.
  - – Should allow the full beam fuelling to be pumped.
- Calculation then benchmarked against SOLPS



Physics Studies are Transferring to the Initial Engineering Design in Collaboration with MIT

- Initial in-vessel geometry has been laid out.
  - Pump radius, throat dimensions taken from the modeling.
  - Is a significant perturbation, requiring a rebuild of basically the entire lower outer divertor.
- Specification in progress for the Liquid He refrigerator.
  - Likely suitable model found
  - Location in room adjacent to NSTX-U has been identified.
- Ex-vessel liquid He plumping and transfer Dewar is under design.

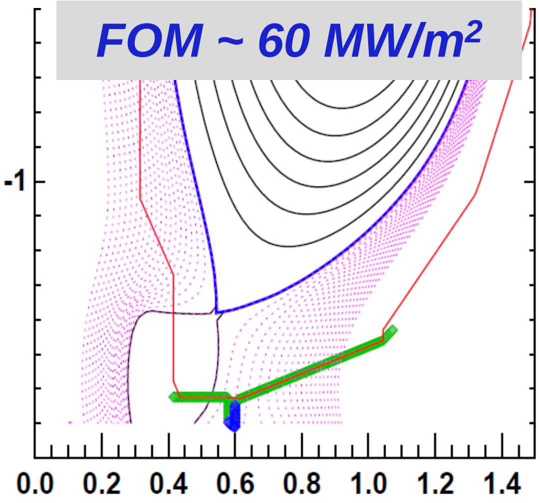



Transfer line layout

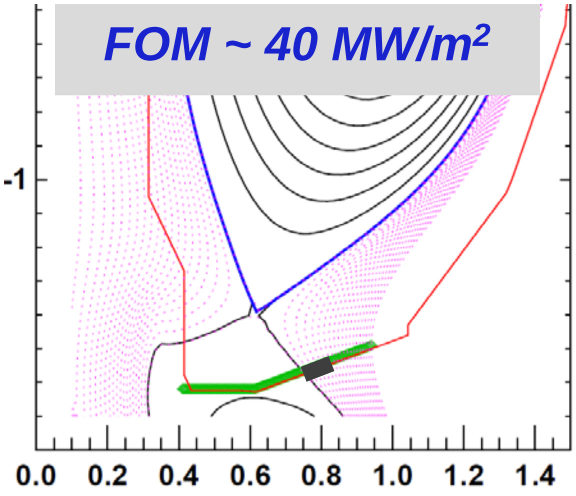
Outboard row of high-Z tiles can access high heat-flux, maintain operational flexibility

- Shape developed to perform dedicated tests on outboard PFCs
  - ISOLVER free-boundary solver utilized with specified β_N
  - 0D-analysis obtains heating power for assumed confinement multiplier H_{98y2}
- Zero-radiation power exhaust provides heat flux figure-of-merit (FOM)
  - FOM calculates incident power accounting for magnetic shaping only
  - High-Z shape FOM is 66% of similar full-power, high-triangularity scenario

High-performance discharge

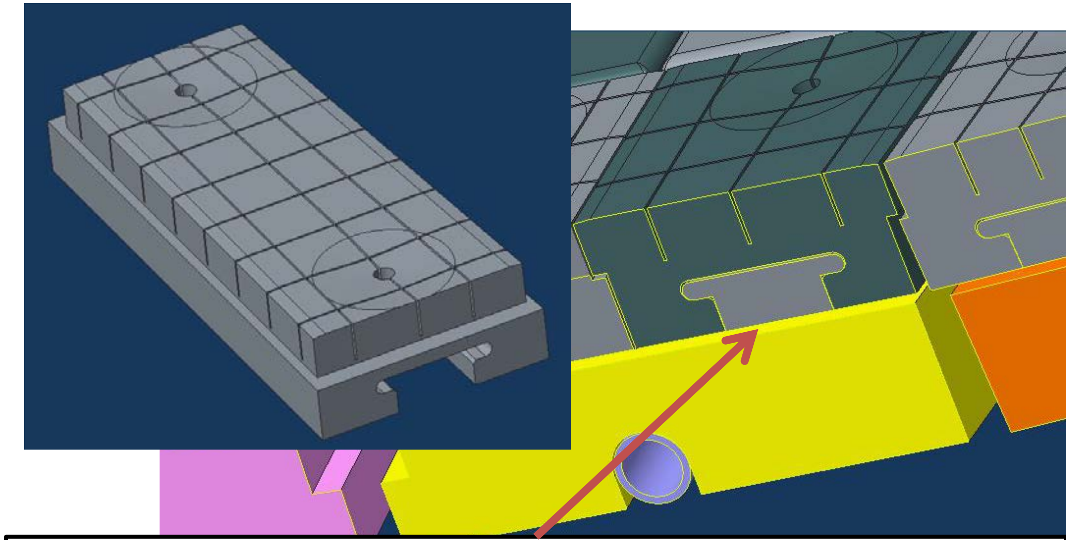

FOM ~ 60 MW/m²

High-Z reference discharge


FOM ~ 40 MW/m²

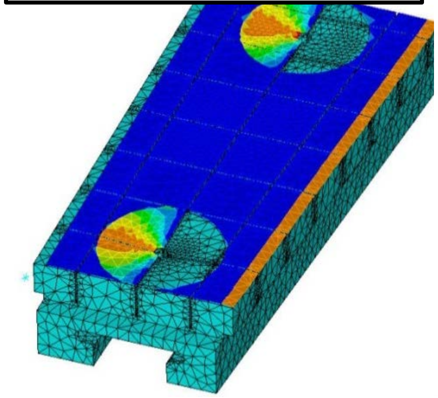
Single row of TZM molybdenum tiles will be installed for the FY-2017 run campaign

- Goals:
  - Initial assessment of plasma performance with high-Z PFC
  - Develop expertise in analysis, manufacture, installation with the new material
- Design constrained to by a one-for-one replacement of the existing tiles.
- Raw material procurement underway
- Edge and access-way chamfers introduced to reduce heat-flux peaking.

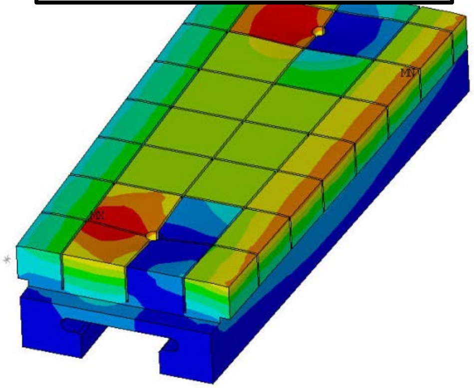


Seamless integration with existing mounting scheme minimizes installation time

Surface heat flux



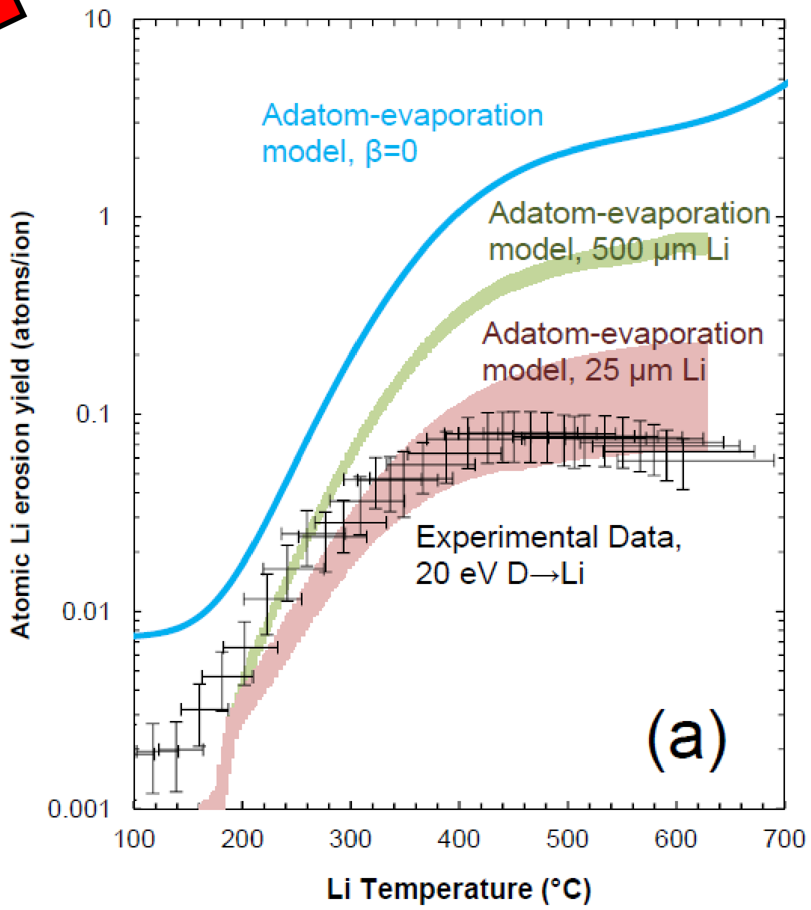
Temperature



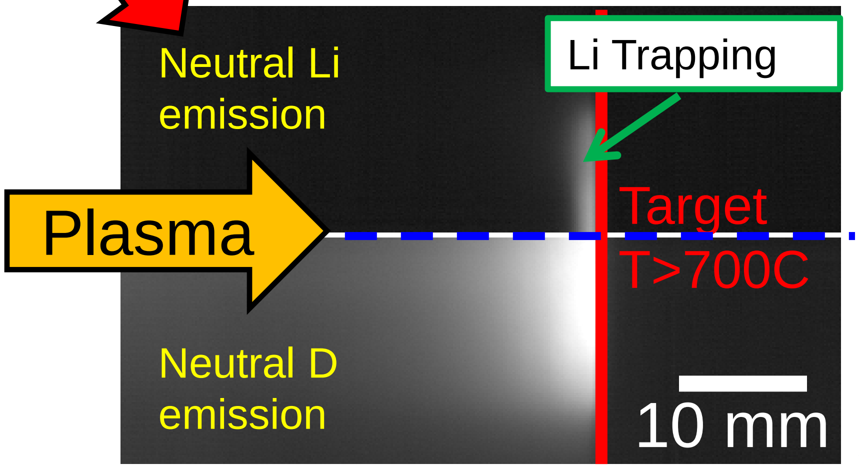
Suppressed erosion and trapping at target observed in linear plasma device (Magnum-PSI)

- Mixed-material effect reduces erosion due to LiD formation
- Plasma pre-sheath potential well large enough to retain eroded Li
- Significant implications for evaporative cooling concepts

T. Abrams 2014 PhD Princeton U.,
T. Abrams 2016 Nucl. Fusion,
M. Chen 2016 Nucl. Fusion.



Li-I emission, t=2.5s



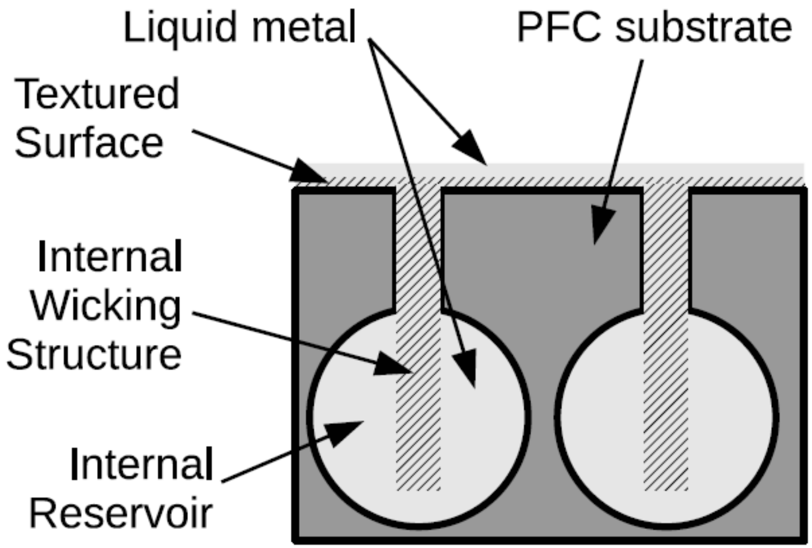
Jaworski, 3rd ISLA, 2013

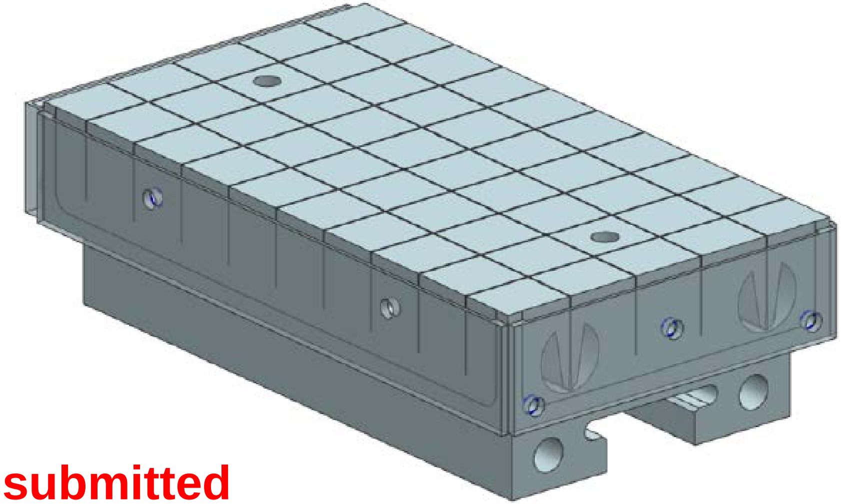
Pre-filled target concept integrates Li reservoir with high-Z tile scheme

- Similar to CPS device but applicable as divertor PFC

- Utilizes wire-EDM fabrication to obtain complex geometry

- Emphasizes passive replenishment via capillary action

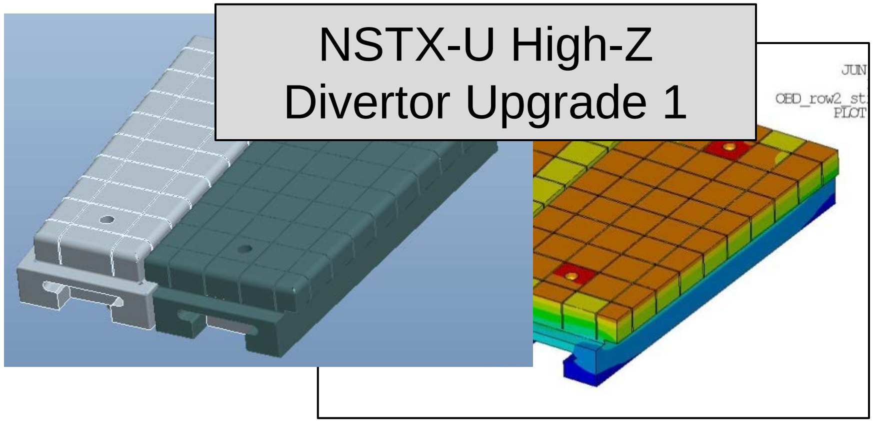




P. Rindt, TU/Eindhoven Thesis, Jaworski FED submitted

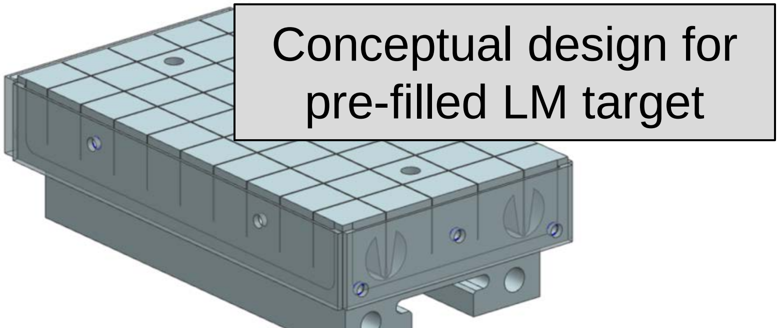
A three-step progression can achieve flowing, liquid metal PFCs

1. High-Z divertor tiles + LITER



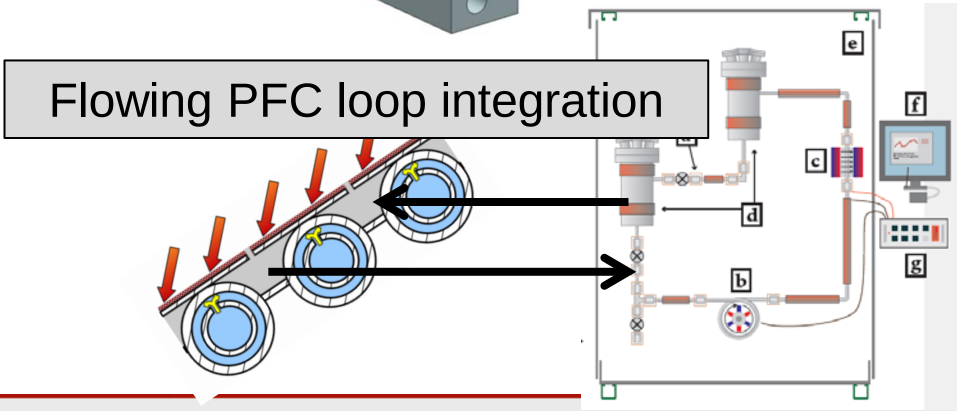
NSTX-U High-Z Divertor Upgrade 1

2. Pre-filled liquid-metal target



Conceptual design for pre-filled LM target

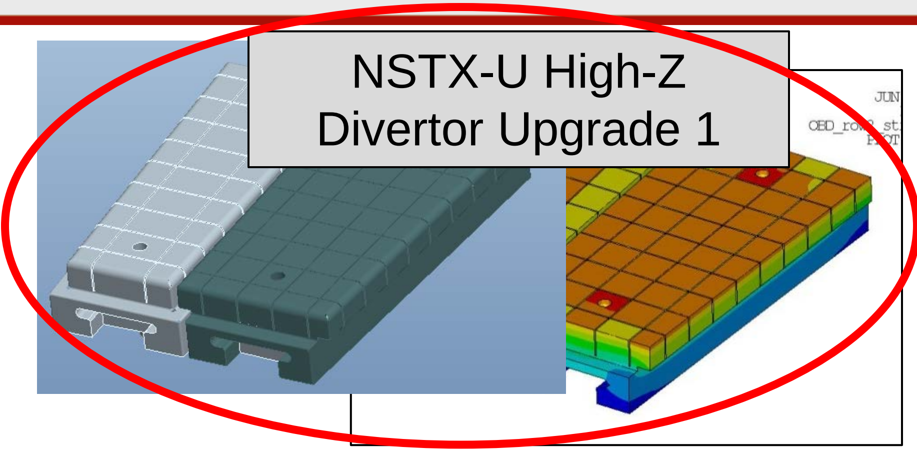
3. Flowing LM PFC

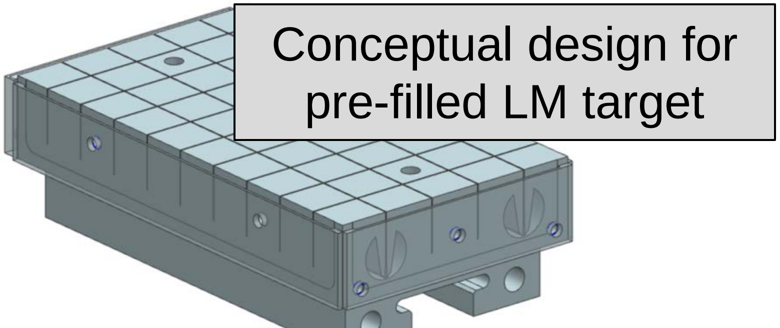


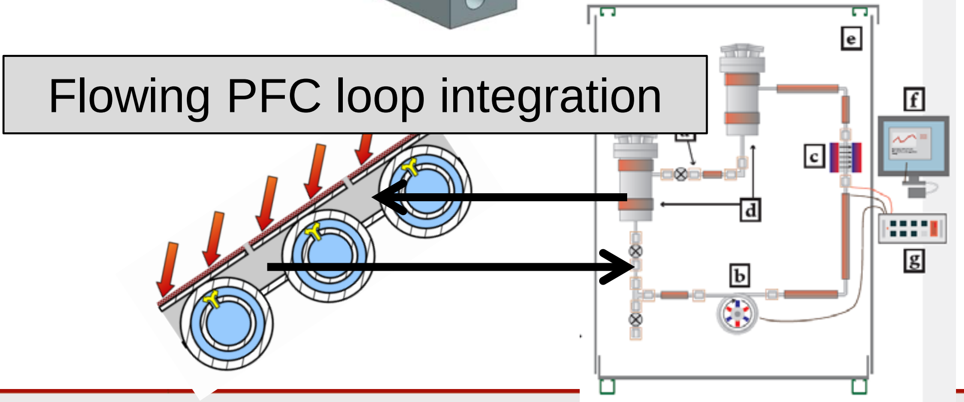
Flowing PFC loop integration

High-Z divertor tiles + Li evaporated coatings provide divertor analogue of Magnum-PSI experiments

1. High-Z divertor tiles + LITER
   - Technical goals:
     - Establish non-intercalating substrate for evaporated Li
     - Provide high-heat flux substrate for Li experiments
   - Scientific goals:
     - Quantify maintenance of Li on high-temperature substrate and protection of substrate
     - Re-examine suppression of erosion in high-flux divertor
     - Understand impact and core-edge compatibility of high-temp. target with limited inventory of Li

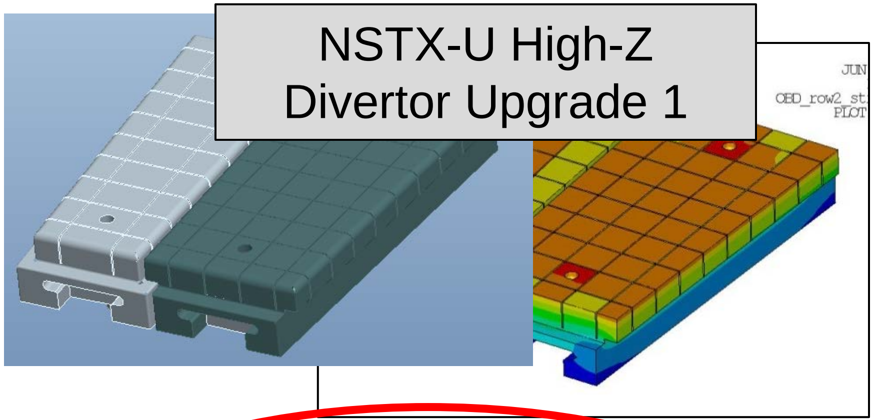

NSTX-U High-Z Divertor Upgrade 1

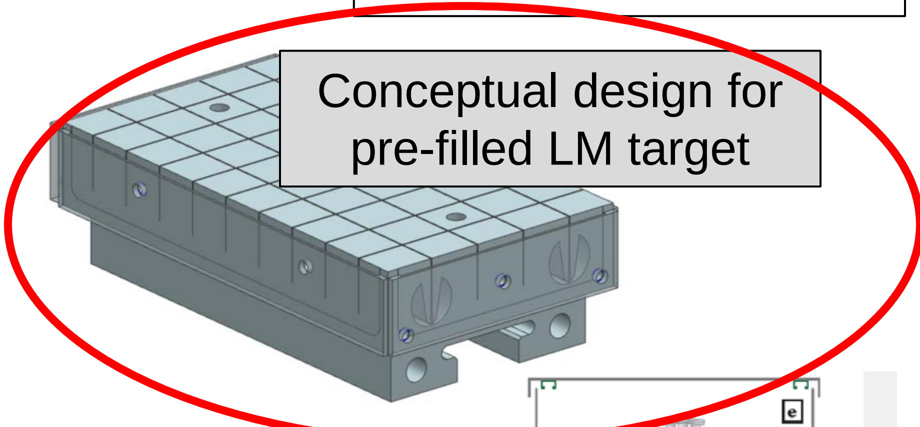

Conceptual design for pre-filled LM target

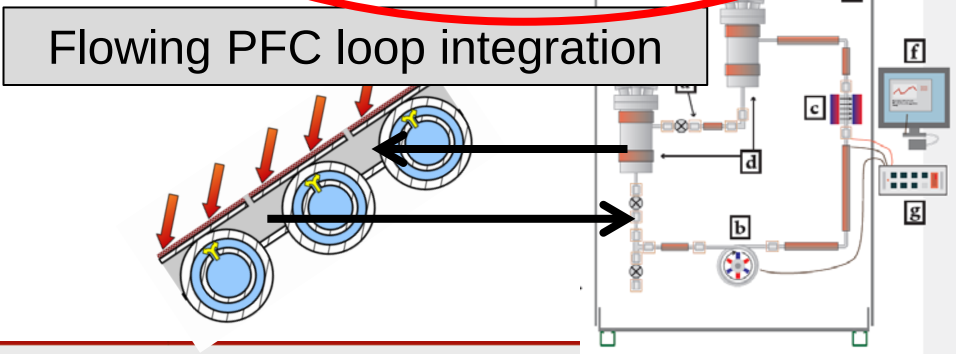

Flowing PFC loop integration

Pre-filled targets test LM coverage, resupply and impact of significant Li source

2. Pre-filled liquid-metal target
   - Technical goals:
     - Achieve introduction of Li in NSTX-U without evaporation
     - Realize complex target production as high-heat flux target
   - Scientific goals:
     - Test models of maintenance of LM wetting and coverage
     - Understand limits of LM passive resupply
     - Understand impact and core-edge compatibility of <u>high-temp. target</u> with **larger** inventory of Li


NSTX-U High-Z Divertor Upgrade 1

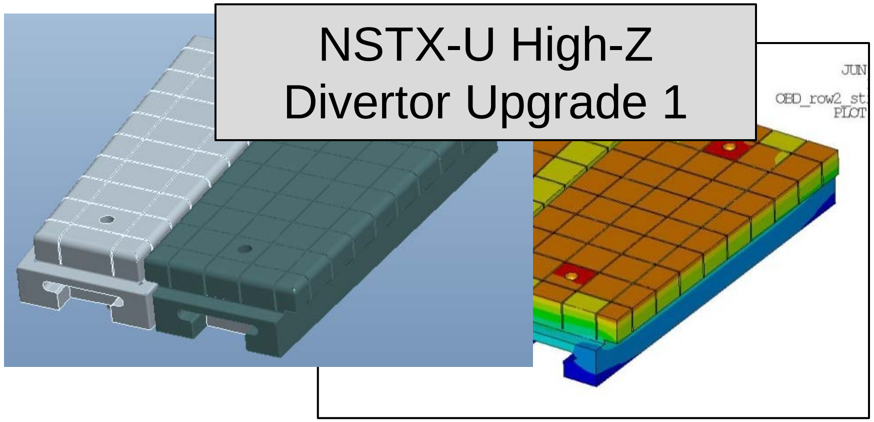

Conceptual design for pre-filled LM target

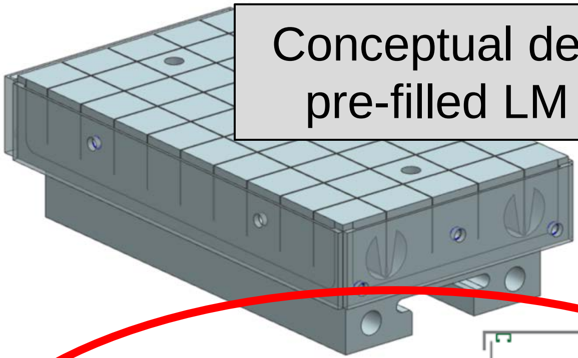

Flowing PFC loop integration

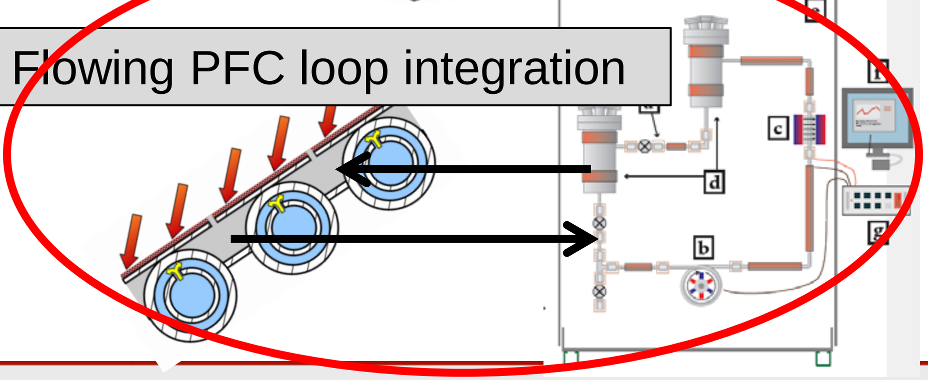
Final integration demonstrates LM introduction/extraction and inventory control

3. Flowing LM PFC

- Technical goals:
  - Integrate parallel effort on loop technology with confinement experiment
  - Achieve active introduction and extraction from exp.
- Scientific goals:
  - Assess material inventory control from LM target
  - Understand performance of passive + active replenishment techniques
  - Understand impact and core-edge compatibility of <u>high-temp. target</u>

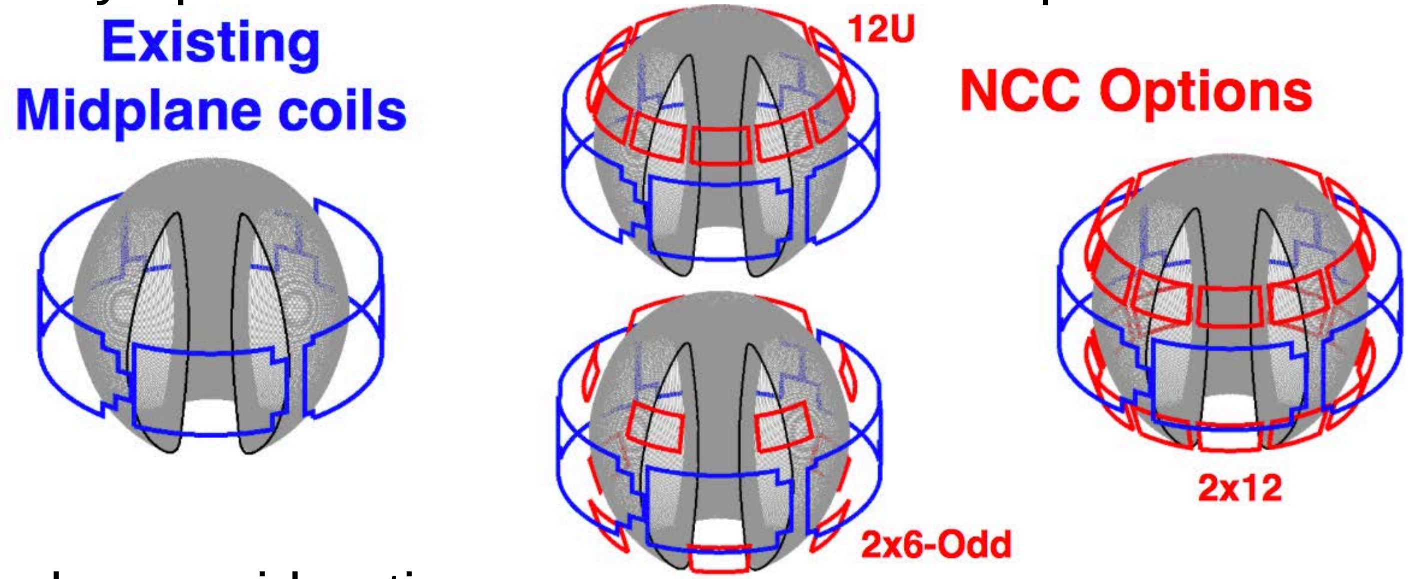

NSTX-U High-Z Divertor Upgrade 1


Conceptual design for pre-filled LM target


Flowing PFC loop integration

Non-Axisymmetric Control Coils (NCC) will dramatically improve NSTX-U 3D physics capabilities

- Three primary options considered for the NCC implementation:

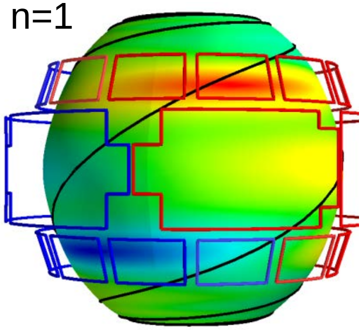


- Metrics under consideration:
  - n=1
    - RWM control
    - Ability to scan the relative ratio of resonant to non-resonant n=1 contributions
  - n>1
    - Variation of available NTV torque profiles.
    - NTV normalized to the Chirkov parameter
- Conclusion: 2x12 is best, 2x6-Odd is a good step in a staged implementation

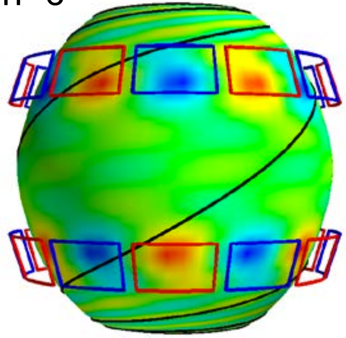
NCC physics design completed: Optimization for NTV braking performed with IPEC coupling matrix

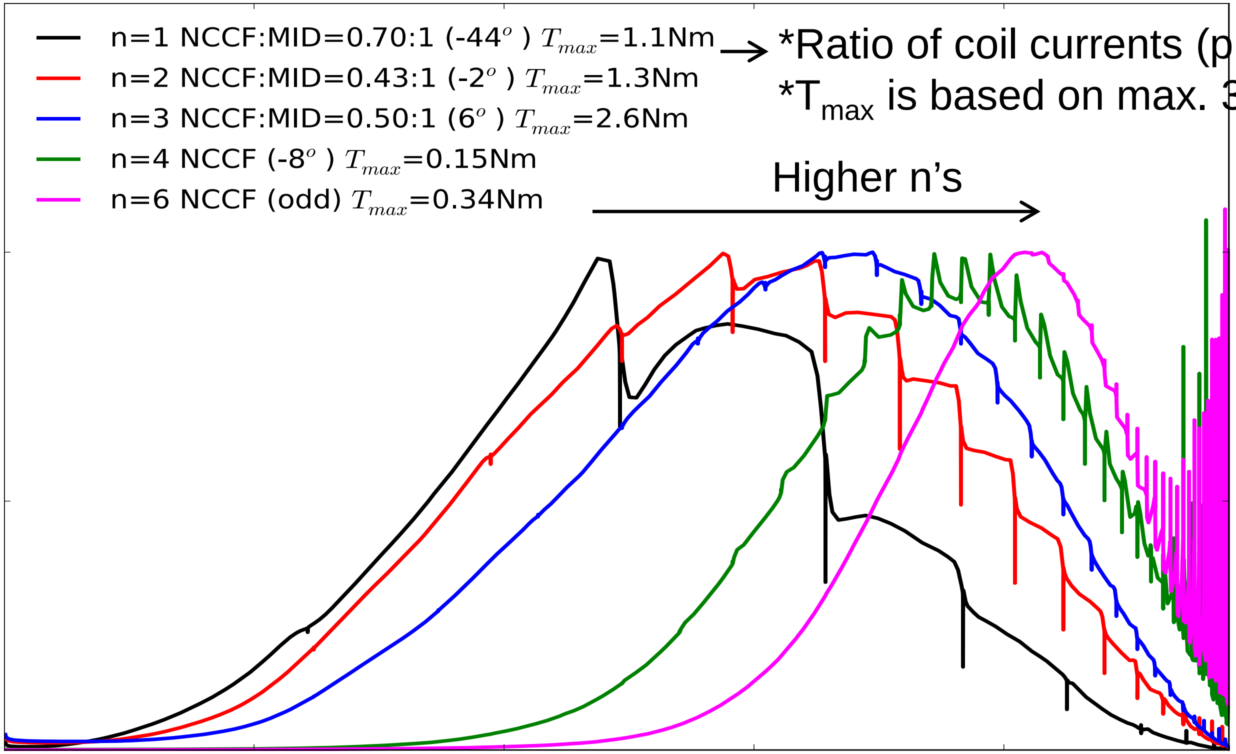
- NCC and midplane coils can be combined to remove the dominant resonant modes up to the second, giving the optimized NTV for core
  - NCC 2x12 provides n=1,2,3,4,6 optimized NTV, and 2x6 provides n=1,2,6
  - Optimized NTV can be used to control local torque with minimized resonance

n=1



n=6



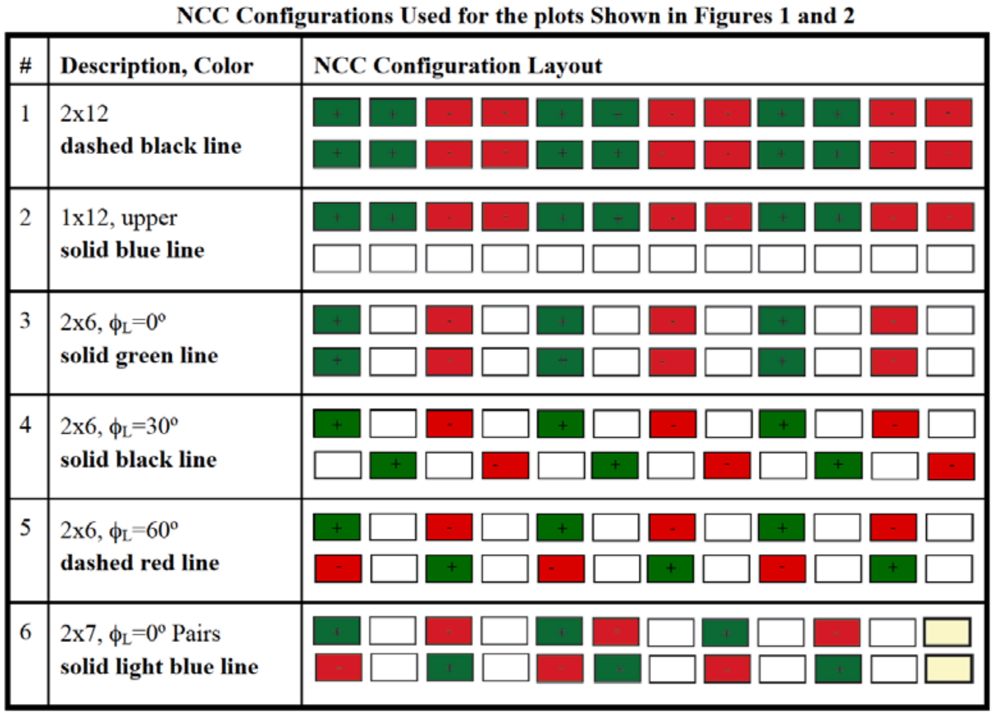


*Ratio of coil currents (phasing)

*T_{max} is based on max. 3kAt

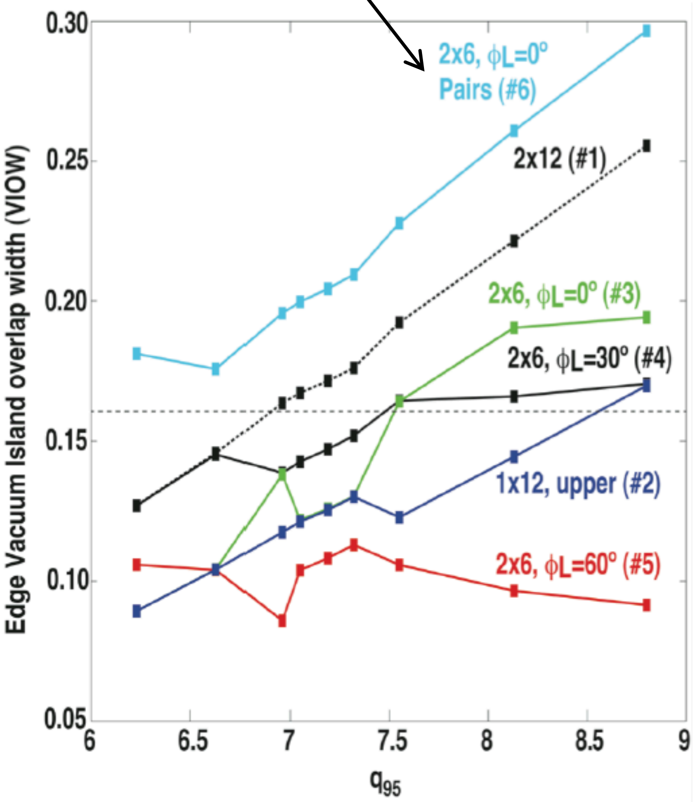
Study of RMP characteristics with NCC extended with TRIP3D (T. Evans) – 2x12 NCC (and 2x7) favorable for RMP

- Vacuum Island Overlap Width (VIOW) analysis shows full NCC 1kAt can produce sufficient VIOW in a wide range of q_{95}, but partial NCC needs more currents with low q_{95} targets
  - Also shows 2x7, with “one” more additional array upon partial NCC can provide the greater VIOW by toroidal coupling (n=2,4,9)



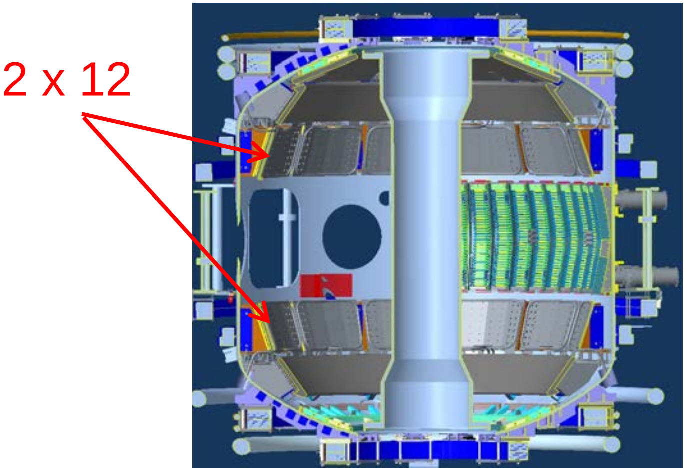
NCC Configurations Used for the plots Shown in Figures 1 and 2

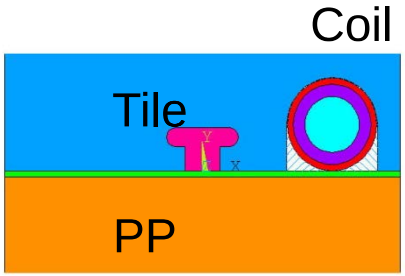
#	Description, Color	NCC Configuration Layout
1	2x12 **dashed black line**	+ + - - + + - - + + - - + + - - + + - - + + - -
2	1x12, upper **solid blue line**	+ + - - + + - - + + - - ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
3	2x6, ϕ_L=0° **solid green line**	+ ☐ - ☐ + ☐ - ☐ + ☐ - ☐ + ☐ - ☐ + ☐ - ☐ + ☐ - ☐
4	2x6, ϕ_L=30° **solid black line**	+ ☐ - ☐ + ☐ - ☐ + ☐ - ☐ ☐ + ☐ - ☐ + ☐ - ☐ + ☐ -
5	2x6, ϕ_L=60° **dashed red line**	+ ☐ - ☐ + ☐ - ☐ + ☐ - ☐ - ☐ + ☐ - ☐ + ☐ - ☐ + ☐
6	2x7, ϕ_L=0° Pairs **solid light blue line**	+ ☐ - ☐ + - ☐ + ☐ - ☐ 🟨 - ☐ + ☐ - + ☐ - ☐ + ☐ 🟨



NCC is Undergoing Conceptual Design in Parallel with the Cryopump

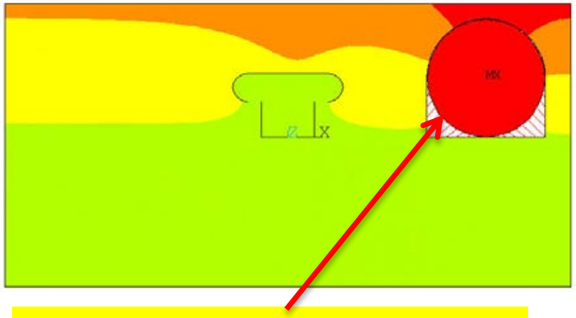
- Considering a mineral insulated conductor
- Order of 20’ test sample is placed:
  - Both solid and hollow center conductors
- Goal is to assess
  - Manufacturability/formability,
  - electrical characteristics, including end-sealing methods,
  - fabrication lead time and cost.
- Hollow conductor will allow He cooling, but analysis indicates thermal ratcheting with solid conductor is likely manageable.





Assumptions In Solid Conductor Calculation

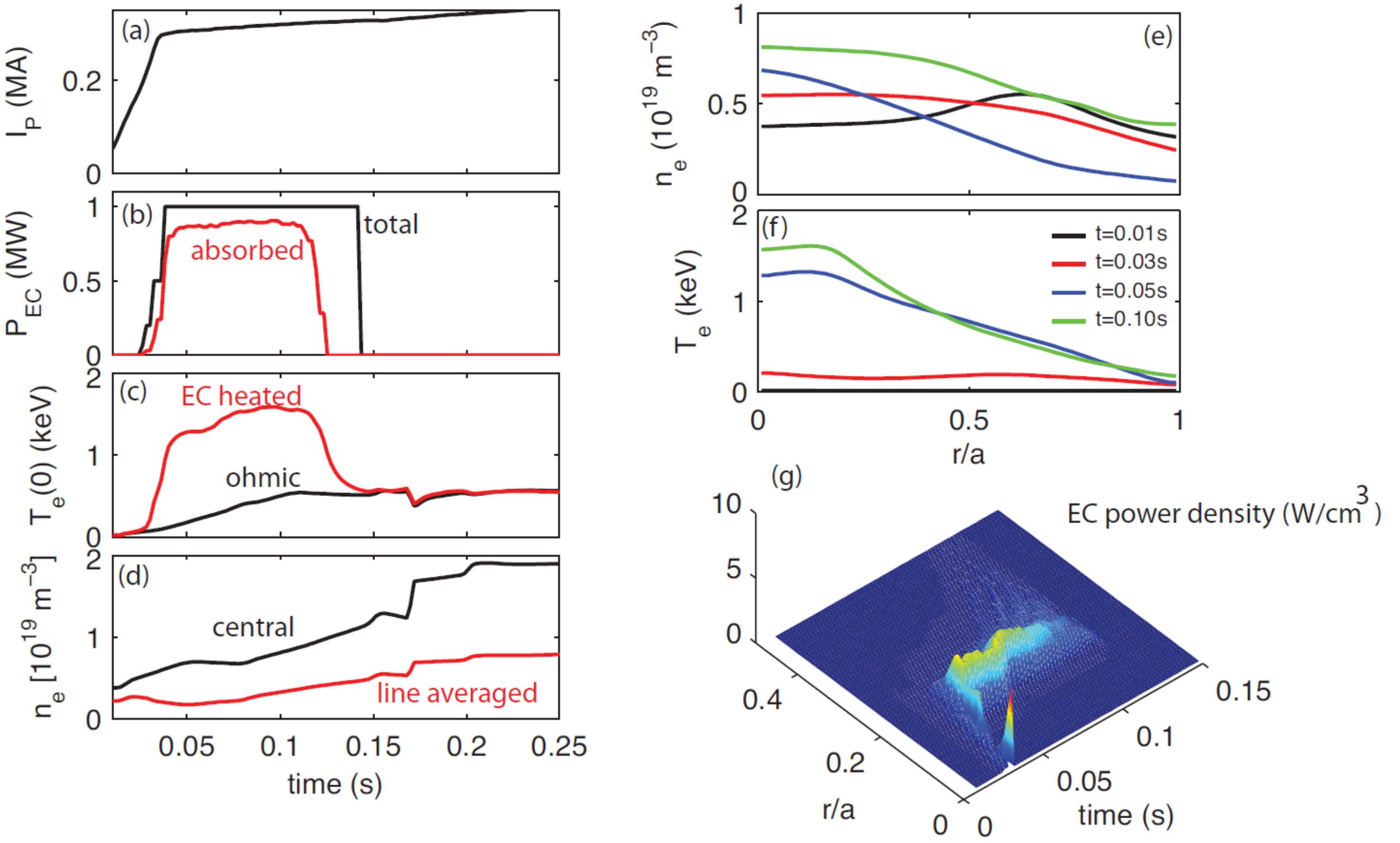
3 kA 5s pulse 1200 s repetition prate



T_{max}=142 C after 8 hours

TRANSP modelling: ECH is game-changer for non-inductive ramp-up

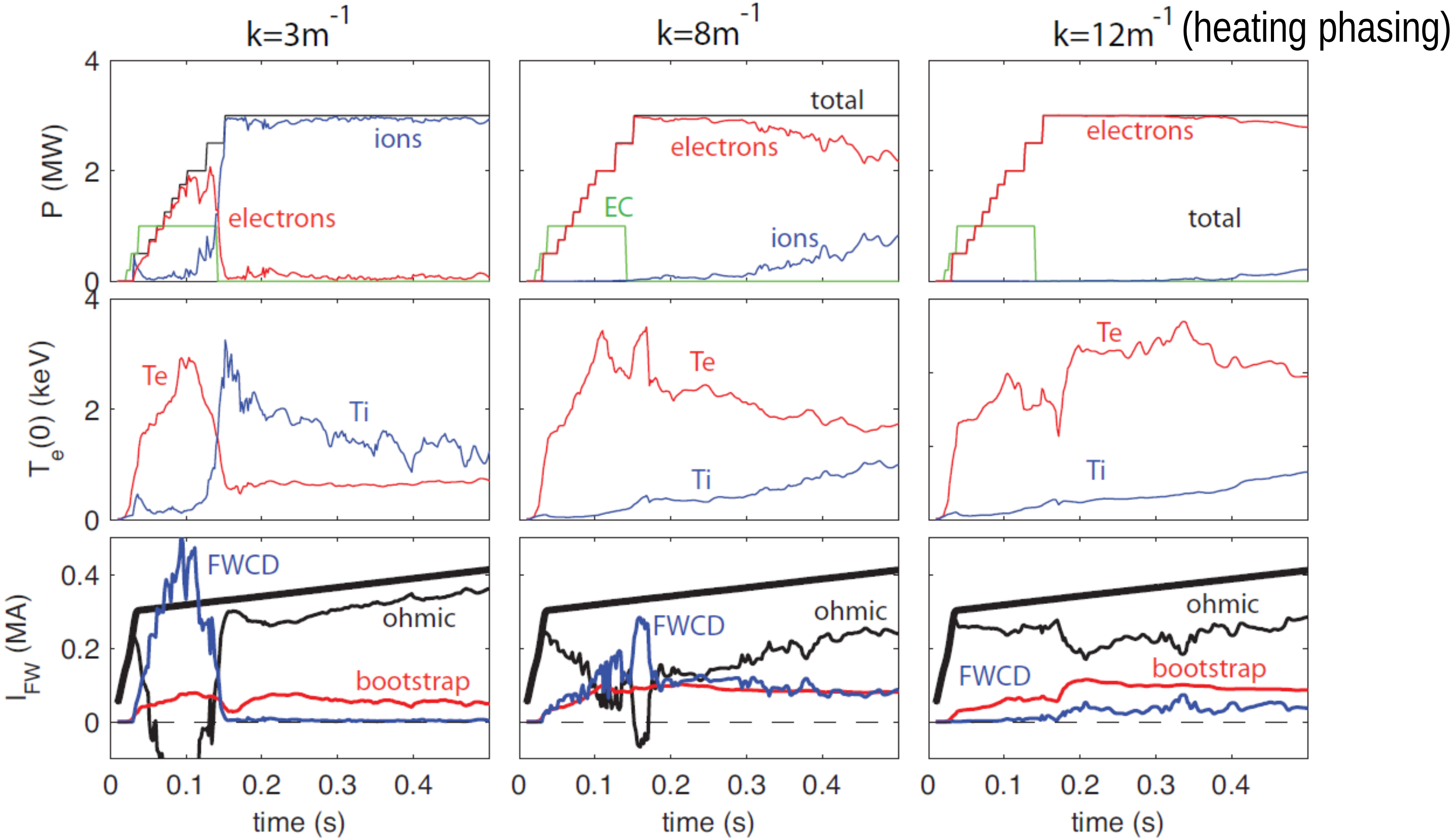
Heats low temperature plasma to 1-1.5keV in ~30ms



ECH accessibility limited to low density, but compatible with CHI

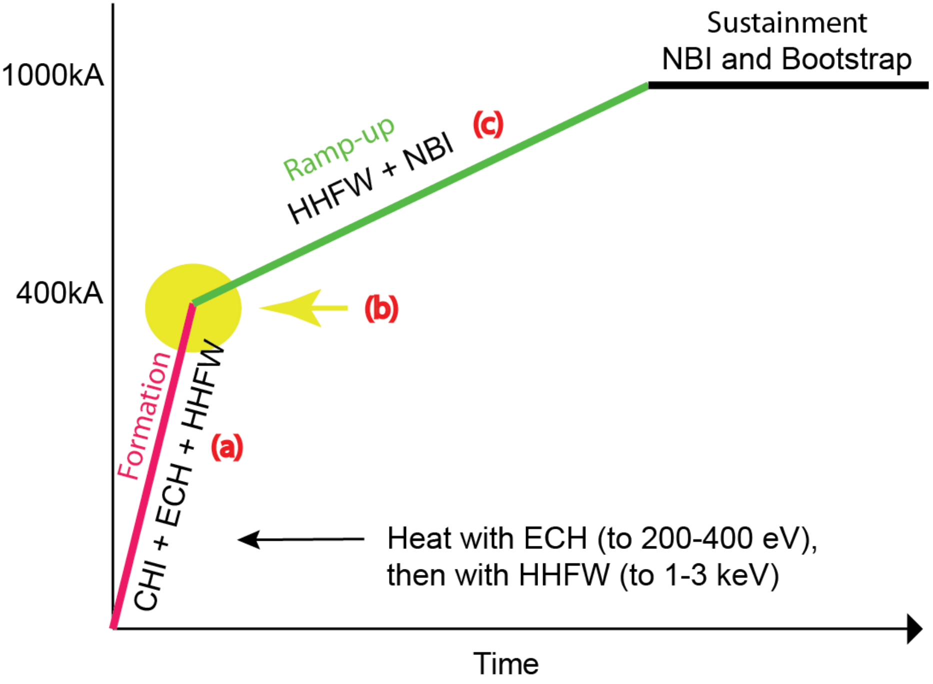
EC + FWCD synergistic for lowest FW phasing k_ϕ=3m^{-1}
Half power needed to drive 400kA compared to no EC

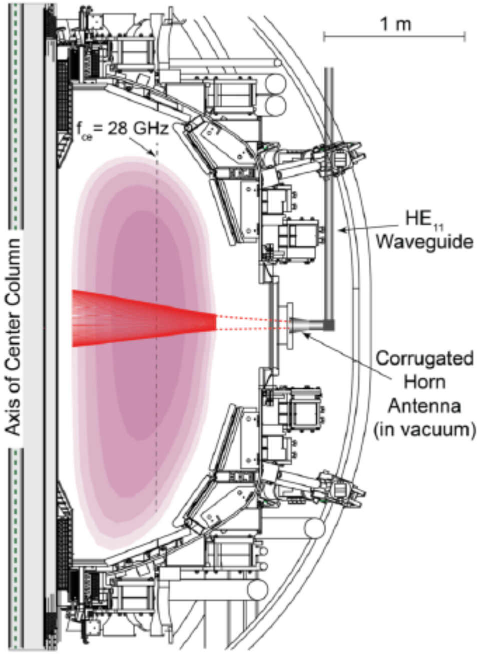
- ECH enables sustained T_e conditions for higher FW k_ϕ
- Need to optimize FW phasing during shot to sustain H&CD

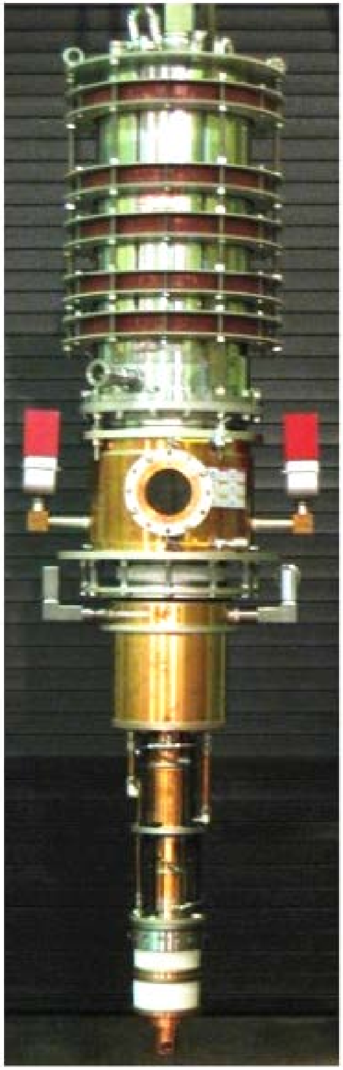


28 GHz Gyrotron System Will Facilitate Non-Inductive Startup Research

- Coupling CHI to NB overdrive will be aided by electron heating







- TSC simulations indicate 0.6MW of absorbed ECH power could increase T_e to ~400eV in 20ms
- 28 GHz, 2 MW tubes developed by Tsukuba University planned to provide this power.
- Have found location for gyrotron, appropriate commercial waveguide manufacturer.